Localization of Submerged Sensors Using a Single Mobile Beacon

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by

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To my Mum & Dad

Statement of Originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Anisur Rahman

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The sacrifices and encouragement of my wife would always be remembered and appreciated. I only wish my son 'Shomoy' and daughter 'Nohor' could have understood why I can't play with them like I used to.

List of Publications

- A. Rahman, V. Muthukkumarasamy, and X. Wu, "Coordinates and Bearing of Submerged Sensors Using a Single Mobile Beacon (CSMB)", *Journal of Networks*, 2015 (accepted)
- A. Rahman, V. Muthukkumarasamy, and E. Sithirasenan, "The Effect of in-situ Underwater Acoustic Speed on Localization of Submerged Sensors" in PhD Forum of *World of Wireless, Mobile and Multimedia Networks (WoWMoM),* 2014.
- A. Rahman, V. Muthukkumarasamy, and E. Sithirasenan, "Localization of Submerged Sensors". Book Chapter: *Nova Publishing Inc*. 2014.
- A. Rahman, V. Muthukkumarasamy, and E. Sithirasenan, "Localization of Submerged Sensors Using Radio and Acoustic Signals with Single Beacon," in *Ad-hoc, Mobile, and Wireless Network*. LNCS. vol. 7960, J. Cichoń, M. Gębala, and M. Klonowski, Eds., ed: Springer Berlin Heidelberg, pp. 293-304, 2013.
- A. Rahman, V. Muthukkumarasamy, and E. Sithirasenan, "The Analysis of Temperature, Depth, Salinity Effect on Acoustic Speed for a Vertical Water Column," in *Distributed Computing in Sensor Systems (DCOSS), IEEE*, pp. 310-312, 2013.
- A. Rahman, V. Muthukkumarasamy, and E. Sithirasenan, "Coordinates Determination of Submerged Sensors Using Cayley-Menger Determinant," in *Distributed Computing in Sensor Systems (DCOSS), IEEE*, pp. 466-471, 2013.
- A. Rahman, V. Muthukkumarasamy, and X. Wu, "Underwater Localization: a pragmatic Approach". *IEEE Communication Magazine of Underwater Wireless Communications and Networks: Theory and Applications*, 2015. (submitted)

Abstract

Unswerving navigation and positioning are becoming imperative in more and more underwater applications for the sustenance of flora and fauna of our marine biome. As marine life helps determine the very nature of our planet at a fundamental level, it becomes crucial to obtain accurate environmental data by using underwater sensors to enable the provision of underwater sanctuary areas. In addition, an underwater wireless sensor network (UWSN) is envisioned to enable application for offshore exploration for the profusion of the wealth underwater world has. It is not only monetary value, it is also deemed necessary to introduce controlled underwater vehicles for surveillance, to find lost objects and to track pollutants. Due to all these potential factors, researchers have shown fervent interest in exploring and exploiting underwater localization schemes to fulfill the multitude of needs as the time demands. To achieving such, a wide range of sensors are deployed underwater to gather data. Many a times, precise coordinates of the deployed sensors which actuate or collect data are vital, as data without the knowledge of its actual origin has limited value. So, a pragmatic dynamic approach is obligatory to localize submerged sensors precisely with minimal logistics, which will require no preinstalled infrastructure and reference points.

A plethora of techniques has been proposed to determine the coordinates of submerged sensors, each with its own limitations. Preinstalled infrastructure, multiple references and auxiliary nodes are commonly used; whereas a single reference point, like a boat, should suffice to localize the sensors for any problem domain without the complexity and tedium of installing reference points. Moreover, the multilateration technique is used to determine the location of the sensors with respect to three or more known beacon nodes. Furthermore, incorporated nonlinear distance equations are solved by conventional methods whereby degree-of-freedom does not guarantee a unique solution. This thesis investigates the problem of localizing submerged sensors and advocates a closed-form solution to determine the coordinates and bearings of those using only a single beacon node at the surface. The propounded method is capable of continuous localization of submerged sensors with precision, in a dynamic fashion, without a preinstalled

infrastructure or reference points. Moreover, the Cayley-Menger determinant and linearized trilateration are used to determine the coordinates of the nodes where none of the nodes have *a priori* knowledge about its location. Simulation results validate the mathematical model proposed herein, by computing the coordinates of sensor nodes with bearing information; thereby generating 10^{-12} to 10^{-14}m positional error with 0.972% variation in bearing with Euclidean distance.

Underwater distance determination between the beacon and sensor nodes is an important factor in localization; and the use of acoustic signals has been the proven technology so far. Usually, the bouncing technique or two-way message transfer is used to measure the distances from beacon to sensors. In fact, the bouncing technique requires lowering a reflector to a specific height, and the two-way message transfer method lacks time synchronization. In both cases, measured distances and the unreliable time synchronization are subject to a huge degree of error. Moreover, a default acoustic speed is considered, regardless of problem domain, which also upsurge the errors in coordinate determination. To minimize such distance determination error, a new method has been devised here, in which *in-situ* acoustic speed is determined from the gathered environmental variables (i.e. temperature, depth and salinity) from the vicinity of beacon and sensor nodes. Therefore, due to the different nature of problem domain, the acoustic speed varies and provides more accurate localization. It is logical to consider that with the advent of incorporating 4th generation computing into the sensors; it is now indispensable to reconsider the use of underwater radio to some extent. As such, the method uses radio signals for time synchronization between the beacon and underwater sensors; and it measures the flight time of generated acoustic signals from the beacon to the sensors. Simulation results show *in-situ* determination of acoustic speed for various problem domains with different combinations of environmental variable varies from 1499.8-1507.6m/s and the experimental results also confirm the potential of determining flight time of acoustic signals between two nodes.

This research could be extended to address and consider the mobility of the submerged sensors while localizing. Voluntary or involuntary mobility can be analyzed to find the Doppler effect, as UWSN is more susceptible than WSN. Therefore, mobility introduces another challenge from the view point of communications overheads and energy-efficiency, since underwater equipment is expected to be left in the ocean for several weeks or months before it is collected and recharged for the next mission. Another interesting research direction could be – inventing sensors and methods which can detect lower radio signals and can be capable of better communication, so that all communications can be replaced by radio instead of acoustic signals as done conventionally.

To conclude, the model delineates the determination of *in-situ* underwater acoustic speed; as well as the coordinates and bearings determination in a pragmatic fashion with a single beacon. Scrupulous accuracy in simulation and experimental result shows the potential of proposed model in coordinate determination of submerged sensors with a single beacon.

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Acronyms

3DUL	3D Underwater Localization
3D-MALS	3D Multistage Area Localization Scheme
ALS	Area-based Localization Schemes
AHLoS	Ad-Hoc Localization System
AoA	Angle of Arrival
APS	Ad-hoc Positioning System
ARTL	Asymmetrical Round Trip based Localization
ASN	Acoustic Sensors Network
AUV	Automated Underwater Vehicle
CLS	Collaborative Localization Scheme
DET	Detachable Elevator Transceivers
DHL	Density-aware Hop-count Localization
DNR	Dive and Rise
DV-Hop	Distance Vector Hop
EERS	Energy Efficient Ranging Scheme
EKF	Extended Kalman Filter
EMI	Electromagnetic Interference
ESPRIT	Estimation of Signal Parameters by Rotational Invariance Techniques
ETA	Elapsed Time on Arrival
GDP	Geometric Dilution of Precision
GPS	Global Positioning System
HLS	Hyperbola-based Localization Scheme
INS	Integrated Network System
LDB	Localization with Directional Beaconing
LOS	Line of Sight
LSHL	Large-Scale Hierarchical Localization
LSL-DET	Large Scale Localization-DET
LSLS	Localization Scheme for Large Scale

MASL	Motion-Aware Self-Localization
MCM	Meandering Current Mobility
MDS	Multi-dimensional Scaling
MEMS	Micro-Electro-Mechanical Systems
MFALM	Multi-frequency Active Localization Method
ML	Maximum Likelihood
MLE	Maximum Likelihood Estimation
MLSL	Maximum-Likelihood Source Localization
MMAE	Minimum Mean Absolute Error
MMSE	Minimum Mean Squared Error
MRP	Message Report Package
MSAUV	Multi Stage AUV
MSDNR	Multi Stage DNR
MUSIC	Multiple Signal Classification
NDLP	Node Discovery and Localization Protocol
NLOS	Non Line of Sight
PCA	Principal Components Analyses
PF	Probabilistic Fingerprinting
PLM	Probabilistic Localization Method
PM	Pattern Matching
PFLS	Particle Filter based Localization Scheme
RBS	Reference Broadcast Synchronization
RF	Radio Frequency
RF-EM	Radio Frequency-Electromagnetic
RLA	Reactive Localization Algorithm
ROV	Remotely Operated Vehicle
RSMB	Range-free Scheme based on Mobile Beacons
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RWP	Random Way Point
SBE	Sequential Bayesian Estimation
SDME	Sufficient Distance Map Estimation
SIM	Selective Iterative Multilateration

SLMP	Scalable Localization scheme with Mobility Prediction
SLUM	Silent Localization Using Magnetometers
SNR	Signal to Noise Ratio
TDoA	Time Difference of Arrival
ToA	Time of Arrival
UDB	Using Directional Beaconing
UPS	Underwater Positioning Scheme
USP	Underwater Sensor Positioning
UUV	Unmanned Underwater Vehicle
UWB	Ultra Wide Band
UWSN	Underwater Wireless Sensors Network
VLF	Very Low Frequency
WLAN	Wireless Local Area Network
WPS	Wide Coverage Positioning System
WSN	Wireless Sensors Network

Chapter 1

INTRODUCTION

Underwater wireless sensor networks (UWSN) are envisioned to enable applications for oceanographic data collection and offshore exploration for the profusion of wealth the underwater world possess. Despite varieties of UWSN applications, the idea of submerged wireless communication may still seem far-fetched and therefore, has attracted researchers in the last decades [1]. In addition to underwater sensors, UWSNs may also comprise of surface stations and autonomous underwater vehicles; the usual number of sensors deployed underwater to collect location based data varies from several to thousands. Often the collection of data and the monitoring of the deployed sensors need to be done in a dynamic fashion, if possible without a preinstalled infrastructure. Having a single boat or mobile station at the surface of the water to collect data, or to monitor and control the deployed underwater nodes is a practical configuration. It is conspicuous that locations of submerged sensors play a vital role in the significance of data validity, hence determining the coordinates precisely is crucial. The many distance measurement techniques for terrestrial application based on signal strength, but these algorithms are not readily suitable for the underwater environment because of a number of factors associated with these methods.

While various localization algorithms have been proposed for terrestrial wireless sensor networks (WSN), there are relatively few efficient localization schemes for UWSN, where most of them deviated from the pragmatic approach. The characteristics of underwater sensor networks are fundamentally different from those of terrestrial networks. Conventional underwater localization mainly performed with the use of acoustic signals since radio waves do not propagate well; despite the fact that the acoustic channel is characterized by harsh physical environments with stringent bandwidth limitations. Moreover, the variable speed of sound and the long propagation delays pose a unique set of challenges for localization in UWSNs. The localization schemes that use reference nodes can be broadly classified into two categories: range-based schemes (schemes that use range or bearing information), and range-free schemes (schemes that do not use range or bearing information). The former apply inter-node distances to multilateration or triangulation whereas the latter rely on profiling. In range based schemes, range measurement using acoustic signals are considerably more accurate with additional distance measurement hardware [2, 3].

Despite the limitations in both radio and acoustic signals in underwater environments, we propose to exploit to our advantage the merits of each in order to minimize distance measurement errors associated with timing, while at the same time compensating for coverage area. If the problem domains are within a depth of 200 meters, which covers most shallow water, the limited range of radio signals will not affect our localization endeavor. In our method, radio signals will be used to measure the flight time of the acoustic signals for determining *in-situ* underwater acoustic speed for a vertical water column; similarly, the acoustic signals will indirectly be used for communication purposes. Even though the speed of radio signals underwater is little less than that in a vacuum ($\approx 3\times10^8$m/s), in relation to the problem domain, the variation in speed will not have significant effect on the proposed localization method. Moreover, the speed of acoustic signals which varies due to a number of factors, namely, temperature and salinity variation of the water between the surface node (beacon) and deployed underwater sensors, and depth of the water column. Therefore, to determine the coordinates in a dynamic adhoc manner, a mechanism to calculate the *in-situ* average acoustic speed for coordinate determination will also be devised.

In our proposal, a single beacon is used to determine the coordinates of the sensors. Having a mobile beacon, i.e. a boat, is more pragmatic than having multiple beacons in the localization process. To determine the coordinates of these sensors in such a dynamic configuration that has no preinstalled reference point, the proposed mathematical model first partially incorporates the Cayley-Menger determinant, followed by linearization to solve a system of non-linear equations produced by the determinant. To simplify procedures, it is assumed that the submerged sensors are static during the time of computation – the time required to measure the distances of the sensors from different positions of the beacon. A solvable configuration of one beacon with three submerged sensors is denoted in section 4.2. The model computes the coordinates and the bearings with respect to the beacon node which alleviates a number of problems in the domain of localization. Simulation results suggest that if the distances between the beacon and the sensors are true Euclidean, then the positional errors are negligible. For a problem domain of 150m depth, positional theoretical errors found are in the 10^{-12} to 10^{-14}m range. Considering the size of the deployed sensors, the generated error is almost negligible, which in turn validates the proposed mathematical model.

1.1 Significance of the Research

Wireless communication applications have become more prominent in the terrestrial environment than underwater. While global positioning system (GPS) receivers are commonly used in terrestrial WSNs to achieve location, this is not feasible in UWSNs since GPS signals do not propagate through water. However, in recent years, researchers have shown fervent interest in exploring and fulfilling the needs of a multitude of underwater applications. This is because it can offer significant advantages and benefits in a wide spectrum of aquatic applications: underwater environmental observation for scientific exploration, commercial exploitation, coastline protection, and target detection in military events. Moreover, 70% of the Earth's surface is covered in water, and with this vast resource of marine life, providing food, medicine and raw materials, localization of sensor nodes is indispensable for UWSN. Since marine life helps determine the very nature of our planet at a fundamental level, it is vital to obtain accurate environmental data to provide and maintain sanctuary for marine life by using such underwater sensors.

The importance of underwater localization is enormous in disaster prevention research, where scientists detect the fault movement rate and activities for possible calamity. Moreover, advanced robot navigation and surveillance, autonomous vehicle control, finding lost object, geo-routing, estuary monitoring and pollutant tracking also require accurate localization [2]. Fig. 1.1 shows an arena where localization plays an important role. In addition to underwater sensors, UWSN may also comprise surface stations and autonomous underwater vehicles. Therefore, irrespective of the type of deployment (outdoor, indoor, underground or underwater), the location of sensors needs to be determined for meaningful interpretation of the sensed data [4].

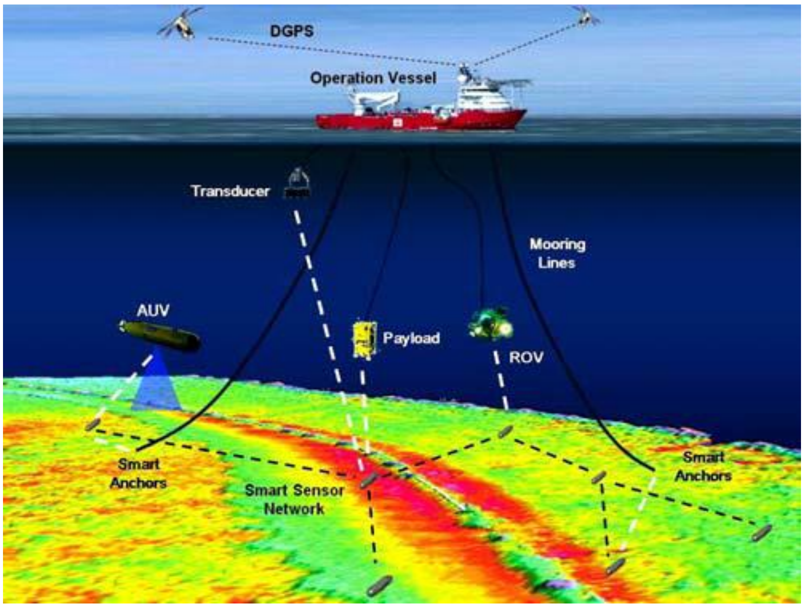

Fig. 1.1 Application scenario for UWSNs

1.2 Problems Definition

As our main objective is to provide a pragmatic approach to determine the coordinates and bearings of the submerged sensors accurately using a single beacon in dynamic fashion, we have identified following deliverables:

1. Determine the distances between the beacon (at the water surface) and the deployed underwater sensors on the fly. Recent studies show that it is possible to use radio signals in underwater environment; by carefully choosing the right frequency for both radio and acoustic signals, we propose an algorithm to determine the flight time of the acoustic signals that eventually avoids and minimize the multipath impact of the signals.
2. Determine the average acoustic speed in a vertical water column efficiently, using the data gathered from the submerged sensors. Derivative of multivariate Mackenzie equation for acoustic speed in a single point can be used to determine average speed for a vertical water column.
3. Design the mathematical model to determine the coordinates and bearings of the sensors from a single point with distance (beacon to sensors) information only. Linearized Cayley-Menger determinant can be used to determine the coordinates of the sensors while the sensors are stationary and in parallel states.

4. Design the model to deal with the parallel plane constraint generated from above mathematical model. It can be addressed by creating a paralleled plane with water surface taking imaginary points.

1.3 Thesis Outline

This report is divided into seven chapters as following:

- Chapter 1 gives a brief introduction, and outlines the major objectives of this report.
- Chapter 2 describes the relevant background of the research topic. It also covers the localization techniques and their limitations for both underwater and terrestrial wireless sensor networks.
- Chapter 3 identifies the research question in the context of limitations described in Chapter 2. It also defines the hypothesis assumed to answer the research questions, and then describes the methodology used to validate the hypothesis.
- Chapter 4 delineates distance measurement techniques and analysis for different problem domain.
- Chapter 5 reports the focus on coordinates and bearing determination of the deployed sensors with a single beacon for parallel and non-parallel states.
- Chapter 6 outlines the experimental results and performance analysis.
- Chapter 7 concludes the outcome of the research and future exploration window in relates to this research endeavor.

Chapter 2

BACKGROUND

This chapter lays out the synopsis of past research and studies, as well as the critical reviews of articles from relevant literature. It also examines some of the problems and limitations of the current systems. The sections of the chapter cover relevant information as following:

- The first section covers terrestrial wireless sensor networks and underwater wireless sensor networks.
- The second and third describes dynamicity of underwater environment and underwater signals (acoustic and radio) propagation issues respectively.
- The fourth and fifth sections examine sensors localization and distance measurement techniques and challenges associated with those.
- The sixth section details the existing localization techniques and limitations.
- The last section summarizes some of the problems and limitations that were identified.

2.1 Wireless Sensor Networks

A wireless sensor network are spatially distributed autonomous sensors to monitor physical and environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data thorough the network to a main location. Modern networks are bi-directional, also enabling control of sensor activity which consists of a potentially large number of sensors. Sensor network applications [5, 6] include tracking, and monitoring public exposure to contaminants. In addition, networked sensors have a broad spectrum of applications in the defense area, generating new capabilities for reconnaissance and surveillance as well as other tactical applications [7]. A WSN may also contain smaller number of control nodes, which may have more resources; however, the sensor nodes are usually resource constrained. Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power and multi-functional sensors that are small in size and communicate in short distances. Cheap, smart sensors, networked through wireless links and deployed in large numbers, provide unprecedented opportunities for monitoring and controlling homes, cities, and the environment. An example of a sensor node is the Mica mote, which contains a 4 MHz processor with 512KB flash memory and 4KB of data memory. A Mica mote also has a separate 512KB flash memory unit accessed through a low-speed serial peripheral interface. The RF communication transfer rate is approximately 40kbps; however, due to communication overhead, the amount of data that is transferred is 19.2kbps. The maximum transmission range is approximately 100 meters in open space.

Communication is the most expensive operation in sensor networks, where the received power drops off as the fourth power of distance mainly due to multipath propagation [8]. If the distance between the nodes is ten meters, every bit sent is equivalent to five thousand operations. Therefore, if the distance between the nodes is one hundred meters, then every bit sent is equivalent to fifty million operations. When transmitting and receiving information encrypted using symmetric cryptography, only two percent of the energy consumed is used to encrypt or decrypt the data [9]. There are many different types of sensor environments, ranging from large areas covered by sensors to many sensors in a small area [5]. Different environments have a wide range of different characteristics. For instance, sensors placed in large open area have got different challenges than sensors placed in underwater; mostly environmental factors and norms associated with the problem domain determine the challenges. Considering the communication medium, WSN can be categorized into two that are discussed in the following sections.

2.1.1 Terrestrial Wireless Sensor Networks

A terrestrial wireless sensor network may compose of a large number of sensor nodes, which are densely deployed either inside the phenomenon or very close to it. Recent advances in micro-electro-mechanical systems (MEMS) technology, wireless communications, and digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances [10]. These tiny sensor nodes, which consist of sensing, processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes. Sensor networks represent a significant improvement over traditional sensors, which are deployed in the following two ways [11].

- Sensors can be positioned far from the actual phenomenon, i.e., something known by sense perception. In this approach, large sensors that use some complex techniques to distinguish the targets from environmental noise are required.
- Several sensors that perform only sensing can also be deployed. In this deployment, the positions of the sensors and communications topology are carefully engineered. They transmit time series of the sensed phenomenon to the central nodes where computations are performed and data are fused.

The position of sensor nodes need not be engineered or pre-determined at all instances. This allows random deployment in inaccessible terrains or disaster relief operations. On the other hand, this also means that sensor network protocols and algorithms must possess self-organizing capabilities. Another unique feature of sensor networks is the cooperative effort of sensor nodes. Sensor nodes are fitted with an on-board processor. Instead of sending the raw data to the nodes responsible for the fusion, sensor nodes use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data.

The above described features ensure a wide range of applications for sensor networks. Some of the application areas are health, military, and security. For example, the physiological data about a patient can be monitored remotely by a doctor. While this is more convenient for the patient, it also allows the doctor to better understand the patient's current condition. Sensor networks can also be used to detect foreign chemical agents in the air and the water. They can help to identify the type, concentration, and location of pollutants. In essence, sensor networks will provide the end user with intelligence and a better understanding of the environment. It is envisioned that, in future, wireless sensor networks will be an integral part of our lives, more so than the present-day personal computers.

Sensor networks may consist of many different types of sensors such as seismic, low sampling rate magnetic, thermal, visual, infrared, acoustic and radar, which are able to monitor a wide variety of ambient conditions that include the following [12].

- Temperature
- Humidity
- Vehicular movement
- Lighting condition
- Pressure
- Soil makeup
- Noise level
- The presence or absence of certain kinds of objects
- Mechanical stress levels on attached objects
- The current characteristics such as speed, direction, and size of an object

Moreover, sensor nodes can be used for continuous sensing, event detection, event ID, location sensing, and local control of actuators. The applications can be categorized into military, environment, health, home and other commercial areas. It is also possible to expand this classification with more categories such as space exploration, chemical processing and disaster relief.

2.1.2 Underwater Wireless Sensor Networks

Underwater wireless sensor networks are expected to support a variety of civilian and military applications. Sensed data can only be interpreted meaningfully when referenced to the location of the sensor, making localization an important problem. While global positioning system receivers are commonly used in terrestrial WSNs to achieve this, this is infeasible in UWSNs as GPS signals do not propagate through water. Acoustic communications is the most promising mode of communication in underwater environments. However, underwater acoustic channels are characterized by harsh physical layer conditions with low bandwidth, high propagation delay and high bit error rate. Here, the techniques and challenges in localization specifically for UWSN and categorize them into (i) range-based vs. range-free techniques (ii) static reference nodes vs. mobile reference nodes, and (iii) single-stage vs. multi-stage schemes.

Common communication architectures for UWSN are shown in Fig. 2.1. In addition to underwater sensor nodes, the network may also comprise surface stations and autonomous underwater vehicles (AUV). Regardless of the type of deployment (outdoor, indoor, underground or underwater), the location of the sensors needs to be determined for meaningful interpretation of the sensed data. Since RF communications are significantly attenuated in underwater[13], the use of the well-known GPS is restricted to surface nodes only. Hence, message exchanges between submerged UWSN nodes and surface nodes (or other reference nodes with known locations) needed for localization must be carried out, usually using acoustic communications. Unfortunately, underwater acoustic channels are characterized by long propagation delays, limited bandwidth, motion-induced Doppler shift, phase and amplitude fluctuations, multipath interference, etc. [13]. These characteristics pose severe challenges towards designing localization schemes that fulfil the following desirable properties:

- **High accuracy:** The location of the sensor for which sensed data is derived should be accurate and unambiguous for meaningful interpretation of data. Localization protocols usually minimize the distance between the estimated and true locations.
- **Fast convergence:** Since nodes may drift due to water currents, the localization procedure should be fast so that it reports the actual location when data is sensed.
- **Low communication costs:** Since the nodes are battery-powered and may be deployed for long durations, communication overhead should be minimized.
- **Good scalability:** The long propagation delay and relatively high power attenuation in the underwater acoustic channel pose a scalability problem where performance is highly affected by the number of nodes in the network. Consequently, an underwater acoustic localization protocol should be distributed, rely on as few reference nodes as possible and the algorithm complexity at each node should be invariant with the network size.
- **Wide coverage:** The localization scheme should ensure that most of the nodes in the network can be localized.

In addition to the above quantifiable properties, practical considerations such as ease and cost of deploying reference nodes and other required infrastructure should be taken into account too.

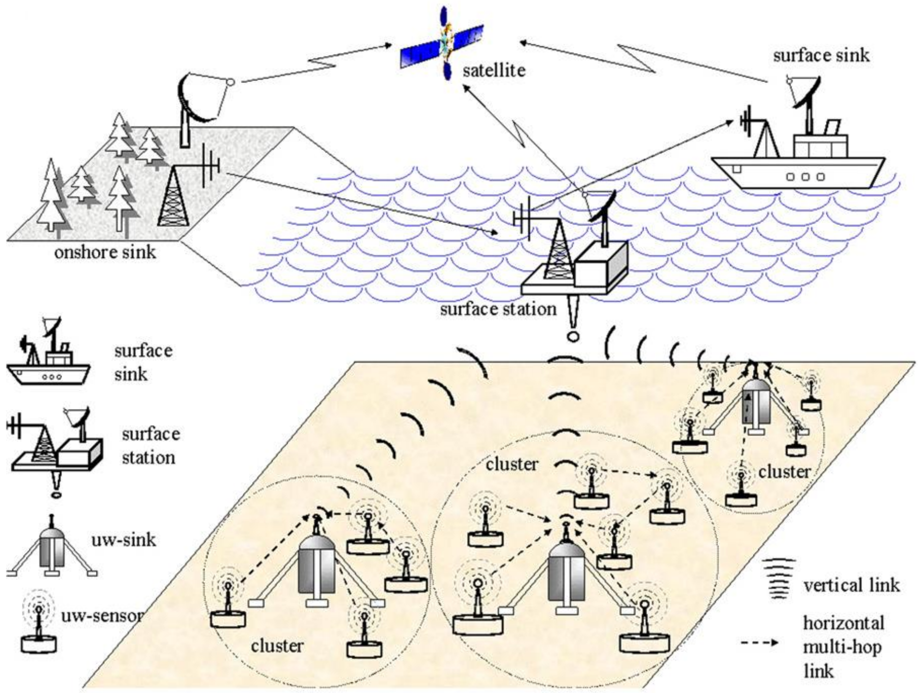

Fig. 2.1 Communication architecture for UWSN [14]

2.2 Dynamicity of Underwater Environment

While node deployment in terrestrial networks is relatively straightforward, the corresponding deployment in underwater environment encounters the following challenges:

- **Reference deployment in deep sea:** To localize underwater nodes deployed in the 3D sea environment, terrestrial localization techniques would require a reference node to be deployed underwater, in addition to references attached to surface buoys. This is challenging, particularly in deep sea applications, where reference nodes may need to be deployed on the seafloor at 3-4km depth. Moreover, as replacement of batteries for submerged modems is difficult, short-range, low-power communication to achieve reasonable data transmission rates is preferred, which may limit the localization coverage.
- **Node mobility:** While it is reasonable to assume that nodes in terrestrial networks remain static, underwater nodes will inevitably drift due to underwater currents, winds, shipping activity, etc. In fact, nodes may drift differently as oceanic current is spatially dependent. While reference nodes attached to surface

buoys can be precisely located through GPS updates, it is difficult to maintain submerged underwater nodes at precise locations. This may affect localization accuracy, as some distance measurements may have become obsolete by the time the node position is estimated. Moreover, motion of the sensor nodes may create the Doppler effect which is due to the relative motion of the transmitter or the receiver. In underwater applications, mobile platforms such as AUVs can move with a speed of several knots, while untethered, free-floating equipment can drift with the ocean currents which are generally slower than 1 knot [15]. Doppler effect is related with the ratio of the relative transmitter-receiver velocity and the speed of the signal. Since the speed of sound in water is slower than speed of the electromagnetic waves in the air, Doppler effect can be more significant in UWSNs than in WSNs. Mobility also mandates that the localization process is repeated at certain intervals so that the node locations do not become obsolete. Therefore, mobility introduces another challenge from the view point of communications overhead and energy-efficiency. Energy-efficiency is required since underwater equipment are expected to be left in the ocean for several weeks or months before they are collected and recharged for their next mission.

Underwater objects are moving continuously with water currents and dispersion. Research in hydrodynamics shows that the movement of underwater objects is closely related to many environment factors, such as the water current and water temperature [16]. In different environments, the mobility characteristics of underwater objects are different. For example, the mobility patterns of objects near the seashore demonstrate a certain semiperiodic property because of tides; but for objects in rivers, their moving behaviors have no such a property. While it is almost impossible to devise a generic mobility model for underwater objects in all environment conditions, some mobility models for underwater objects in specific environments based on hydrodynamics have been devised [17]. This indicates that the movement of underwater objects is not a totally random process. Temporal and spatial correlations are inherent in such movement, which make their mobility patterns predictable in nature. In [18], a case study has been put forward that investigates the mobility characteristics of objects in shallow seashore areas. Tidal areas are characterized by their shallowness and their strong tidal currents. The nonlinear interaction of tidal currents and bottom topography produces currents, which give nonzero contributions to the tidally averaged currents. These so-called residual currents are important for the transport and mixing properties of the tidal flow. Fig. 2.2 shows the velocity of an underwater object with time in a typical seashore environment [18].

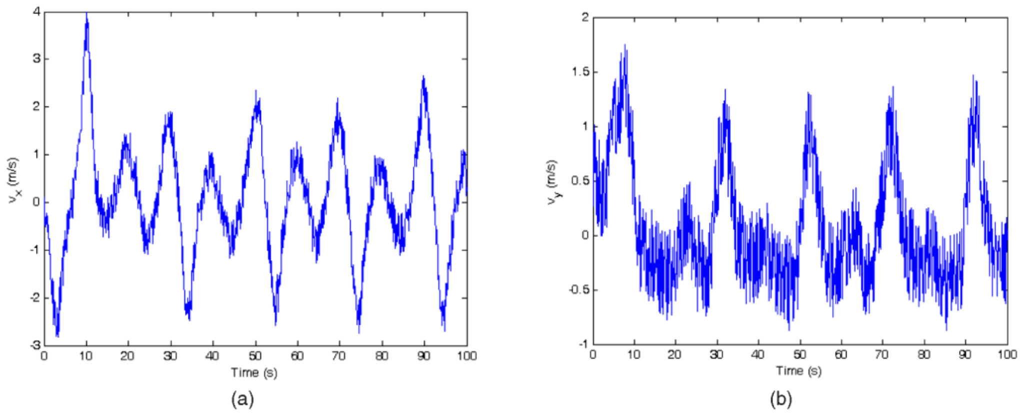

Fig. 2.2 Mobility patterns of objects in a seashore. (a) Vel. in x-axis. (b) Vel. in y-axis

If the mobility of the nodes can be determined, localization process will interpolate the future positions of the nodes from the present positions. Mobility pattern in a specific area can be determined from the study of the area or it can be generalized from the difference of the present and immediate next positions of the nodes in a time frame. This is how mobility pattern can be determined; however this mechanism is going to increase the communication overhead of the localization process.

- **Inter-node time synchronization:** Since GPS signals are severely attenuated underwater, it cannot be used to synchronize time between nodes deployed underwater to compensate for clock drifts due to both offset and skew [4]. Consequently, the accuracy of time of arrival (ToA) based range measurement may be affected. Any scheme that relies on ToA or time difference of arrival (TDoA) requires tight time synchronization between the transmitter and the receiver clocks. One simple way to achieve this in terrestrial networks is to use a radio signal for time synchronization. Kwon et al. [19] use the difference in propagation times of acoustic and radio signals for calculating the distance. This works as the propagation speed of radio signals is multiple orders of magnitude higher than acoustic signals. The luxury of using radio signals for time synchronization is not available in the underwater scenario until recently as radio waves do not propagate well underwater. In [20] it has been shown that it is time to re-evaluate radio signal for the underwater communications. Recently, with the advancement of sensors' sensitivity, we have proposed a scheme to measure the distances between beacon and sensors.

- **Signals reflection due to obstacles and reflective surfaces:** In near-shore or harbor environments, where obstacles may exist between nodes, non-line-of-sight (NLOS) signals are reflected from reflecting object (e.g., sea surface, harbor wall) can be mistaken for line-of-sight (LOS) signals, and may significantly impact the accuracy of range measurement.

2.3 Underwater Signal Propagation

Most underwater wireless networks use acoustic signals as the transmission medium nowadays, which is a proven technology for underwater sensor applications with a long transmission range, but the chances of getting much more out of acoustic modems are quite remote. Another option that may be used for underwater transmission is optical wave, but this only delivers good performance in very clear water, and requires tight alignment due to the demand for the sight and the limitation of very short transmission ranges [21]. The characteristics of optical link have made it impractical for many underwater applications. The latest research on optical UWSNs is depicted in [22]. For the past two decades, wireless multiple-access communications technology based on both radio and optical links have experienced an enormous development. Military and commercial applications of wireless multiple access networks have been more and more in use as advanced electronics and photonic devices become more readily available. Until recently, the successes of these applications have been limited to the terrestrial links because radio-frequency energy is highly attenuated by seawater. However, an underwater wireless network can be implemented based on acoustic or optical communications links [23]. In underwater optical communication, the optical carrier with wavelength λ experiences an exponential total attenuation $c(\lambda)$ due to two optical effects namely photon absorption $a(\lambda)$ and photon scattering $b(\lambda)$ where $c(\lambda) = a(\lambda) + b(\lambda)$, all in units of m^{-1}. Photon energy is lost as a result of interaction with water molecules or other particulates via a thermal process (absorption). Also, photon's path is changed as a result of interaction with particulates (scattering). These two effects reduce the practical communication range to ~100 meters in clear, open ocean waters, and 10's of meters in more turbid, harbor waters [24, 25]. Sometimes unmanned underwater vehicles (UUV) and sensors are deployed to gather important data such as real-time videos which may be of high bandwidth and time sensitive. Therefore, optical links appear to be an attractive alternative when compared to acoustic methods for transmission of large amounts of data with a small delay for short distances. On the other hand, radio propagation through water is very different from propagation through air because of the high permittivity and electrical conductivity of water medium. However, recent studies show significant improvements and open the window of opportunity to utilize radio for communication for limited range. Following sections explore the underwater acoustic and radio signals propagation and recent advancements.

2.3.1 Acoustic Signals

Extensive research and development have been carried out in underwater acoustic networks [26-28]. Acoustics is the proven technology for underwater sensor applications which offers long transmission ranges of up to 20 km [29], although certain challenges and limitations have also been revealed [30, 31]. Acoustic signals yield poor performance in shallow water where transmission can be affected by turbidity, ambient noise, salinity, and pressure gradients; in addition, acoustic technology can have an adverse impact on marine life [32].

Unlike radio frequency (RF) propagation in terrestrial networks, underwater acoustic propagation possesses the following unique characteristics [33].

- **Long propagation delay:** Acoustic speed in water v can be theoretically obtained from the linear wave Eq. (2.1) [34].

$$v = \sqrt{\gamma \frac{B_T}{\rho_0}} \tag{2.1}$$

where γ is the adiabatic index, B_T is the isothermal bulk modulus and ρ_0 is the equilibrium density. The variations of these three parameters with temperature and depth are not easy to predict, so a number of empirical formulas were given in the last decades, for example Eq. (2.2). Since the speed of sound underwater is five orders of magnitude lower than RF propagation over the air, measurement errors due to node mobility may become significant. A typical speed of acoustic waves near the ocean surface is about 1500m/s, more than four times faster than the speed of sound in air but five orders of magnitude smaller than the speed of electromagnetic in air. And the speed of sound v in water can be calculated according to the following Mackenzie [35] empirical equation.

$$\begin{aligned} v = 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \\ + 1.340\,(S - 35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 \\ - 1.025 \times 10^{-2}T(S - 35) - 7.139 \times 10^{-13}TD^3 \end{aligned} \tag{2.2}$$

where T, D and S are temperature, depth, and salinity and constraints for these variables are 2-30˚C, 0-8000m and 25-40ppt respectively.

- **Multipath fading and shadowing:** The underwater acoustic channel is a frequency selective channel with a delay spread of the order of hundreds of taps (a tap refers to the extraction of the signal at a certain position within the channel's impulse response delay-line). Multipath models as well as actual measurements taken from sea trials show that the energy of the direct path of the channel's impulse response is not always the strongest [36]. As a result, multipath (indirect) signals can be mistaken if received signal strength indicator (RSSI) is considered in distance estimation as in Eq. (2.12).
- **Sound speed variation:** Unlike the speed of light which is constant, the speed of sound underwater varies with water temperature, pressure and salinity, giving rise to refraction. Without measuring the sound speed, the accuracy of distance measurements based on time-of-arrival approaches may be degraded. We propose few mechanisms to determine the speed of sound in section 4.2.2 from the *in-situ* environmental variables, which does not require expensive devices that depends on usual bouncing technique.
- **Highly unreliable and asymmetric signal-to-noise ratio:** For a node pair (i, j), the signal attenuation in underwater acoustic channels is widely modelled as Eq. (2.3).

$$TL(d_{ij}) = 10\lambda log_{10}\left(\frac{d_{ij}}{1m}\right) + \alpha d_{ij}\, dB \tag{2.3}$$

where TL is the transmission loss, d_{ij} is the distance from node i to node j, λ is the propagation loss parameter and α is the absorption loss parameter. The parameter, λ depends on the structure of the underwater medium, such that in shallow water or when transmitting from one sound speed layer to another, it can exceed 2, which is a typical value for omnidirectional propagation in free-space. The parameter α increases with the carrier frequency and is affected by the salinity as well as water temperature, among other factors. Since the ambient noise level is depth dependent and decreases with frequency and can be modelled as $50 - log(f)dB$, where f is carrier frequency [37], small variations in f can affect the signal to noise ratio (SNR) significantly. As a result, bandwidth is very limited in underwater acoustic channels and communications links are unreliable. Moreover, nodes i and j may be at different depths, the respective noise levels may be different, giving rise to asymmetric SNR.

- **Asymmetric power consumption:** Unlike RF modems, acoustic modems typically consume much more power (order of tens of watts) in transmit mode compared to receive mode (order of milliwatts). This asymmetry in power consumption makes it preferable for ordinary nodes to be localized through passive/silent listening.

2.3.2 Radio Signals

Underwater radio communications were investigated with fervent interest in the last century up until the 1970s. Because its range is restricted by fundamental attenuation and noise factors that must be considered as unchangeable environmental elements, significant breakthroughs were not to be expected in submarine radio communication [38]; hence, radio communication, although it has notable merits in the terrestrial wireless network field, has had very few practical underwater applications to date. Research on underwater RF communication is currently ongoing, which has been described with examples in [39, 40]. Recent studies shows that radio signal can propagate up to 1.8-323m underwater and the propagation speed can reach up to $4.30x10^6$m/s in MHz frequency [20]. Underwater communication research conducted at Liverpool John Moores University has shown that transmission at 5MHz frequency is feasible in seawater up to 90m giving a data rate of 500kbps that allows duplex video and data streams [41]. Abdou et.al in [42] has shown attenuation of high frequency radio signals in different types of water with various conductivity and they also have emphasized on many advantages of radio signals including bandwidth, data rate, and transmission in cross boundaries with $3x10^7 m/s$ speed. Table 2.1 summarizes the advantages of underwater RF-EM technology [20].

Table 2.1 Summary of advantages of underwater RF-EM technology

Features
Performance • Crosses water to air boundary. Long range horizontal communication using air path, water-to-air or land • Multi-path less of an issue especially in shallow water conditions • Frequency agile capability. No mechanical tuned parts as in an acoustic system • Covert, localized communications. Using high frequency carrier for high attenuation • High Joules per bit efficiency, resulting efficient system for short range and high bandwidth applications • Potential for high data rates. Use of MHz carrier • High propagation speed, important for networking protocols headers exchange
Resistance • Unaffected by pressure gradient. Allows horizontal propagation • Immune to acoustic noise. Operation unaffected by engine noise of heavy work • Unaffected by low visibility. Sediment disturbed at the sea bed has no operational effect while laser systems fail to operate • Immune to aerated water. Operation in surf zone, communication at speed through cavitating propeller wash
Implementation • No need for surface repeater. Crosses water to air boundary for a long range without a surface repeater • Distributed transducers. Radiating cables can deliver unique navigation and communications functions • Compact, portable units. Small-to-medium antennas deliver acceptable performance

As because radio signaling uses a different transmission mechanism than acoustic, it can extend the arena of application; radio signaling, coupled with digital technology and signals compression techniques, has many advantages that make it suitable for niche underwater applications. Even though RF can suffer from limited transmission range and electromagnetic interference (EMI), it also has some valuable features that can enable flexible deployment of UWSNs in coastal regions. Despite the limited underwater propagation distance of radio signals, it possesses some merits. First, both acoustic and optical waves cannot perform smooth transition through air-and-water interface. Radio signals can cross water-to-air or water-to-earth boundaries easily; it follows the path of least resistance, where both air and seabed paths can extend the transmission range. Second, radio transmissions are tolerant to turbulence that is caused by tidal waves or human activities, as opposed to the case of acoustic and optical signals. Third, radio can work in dirty water conditions, while optical waves are susceptible to particles and marine fouling [43]. Fourth, radio operation is also immune to acoustic noise, and it has no unknown effect on marine lives. Table 2.2 outlines three major underwater communication technologies in terms of benefits, limitations and requirements.

Table 2.2 Comparison of underwater wireless communication technologies

	Benefits	Limitations
Radio	• Crosses air/water/seabed boundaries easily • Prefers shallow water • Unaffected by turbidity, salinity, and pressure gradients • Works in non-line-of-sight; unaffected by sediments and aeration • Immune to acoustic noise • High bandwidths (up to 100Mb/s) at very close range	• Susceptible to EMI • Limited range through water
Acoustic	• Proven technology • Range: up to 20km	• Strong reflections and • attenuation when

		transmitting through water/air boundary • Poor performance in shallow water • Adversely affected by turbidity, ambient noise, salinity, and pressure gradients • Limited bandwidth (0b/s to 20kb/s) • Impact on marine life
Optical	• Ultra-high bandwidth: gigabits per sec. • Low cost	• Does not cross water/air boundary easily • Susceptible to turbidity, particles, and marine fouling • Needs line-of-sight • Requires tight alignment of nodes • Very short range

Radio signals propagation through water is very different from propagation through air because of the high permittivity and electrical conductivity of water. Propagating waves continually cycle energy between electric and magnetic fields; hence, high conduction leads to strong attenuation. Besides, plane wave attenuation also increases rapidly with frequency. An important consideration for underwater radio performance is its multi-path propagation feature caused by the effects of the water-to-air interface. Propagation loss and the refraction angle are such that a radio signals crosses the water-to-air boundary and appears to radiate from a patch of water directly above the transmitter. The large refraction angle produced by the high permittivity launches a signal almost parallel with the water surface [44]. This effect aids communication from a submerged station to the land and between shallow submerged stations without the need for surface repeater buoys. A similar effect can also be produced at the seabed. Since the conductivity of the seabed is much lower than water, it can provide an alternative low loss, low noise, covert communications path.

In many deployments, the single propagation path with the least resistance will be dominant. If the air path or the seabed path be chosen as the dominant data path, relatively longer transmission range can be achieved as compared to the water path. Hence the multi-path propagation of electromagnetic waves can be advantageous for signals transmission in shallow water conditions too. All these merits of radio signals encourage us to use radio for time synchronization in distance determination process in section 4.4.

Besides, magnetic coupled loop antennas are the most compact practical solution for duplex submerged systems. Loop antennas are directional in nature and this property can be exploited to allow selection of a single propagation path. Alternatively, Omni-directional antennas can be implemented by crossing two loops so their planes intersect at right angles. Larger loop area will always provide greater antenna gain but practical systems can be designed using relatively compact loops, for instance, a small area loop antenna has been demonstrated in [45]. Another option is to use an electric dipole antenna for lateral electromagnetic waves [46]. In [39], implemented a system using a crossed uninsulated terminated dipole with a diameter of 2cm and 1m in length, which makes careful reciprocal orientation unnecessary, thus simplifying deployment.

Table 2.3 shows the variation of key parameters vs. frequency, which is based on the equations below.

$$\lambda = 1/\sqrt{(f\sigma \times 10^{-7})} \tag{2.4}$$

$$v = \sqrt{(f \times 10^{7})/\sigma} \tag{2.5}$$

$$\delta_{skin} = 1/\left(2\pi\sqrt{f\sigma \times 10^{-7}}\right) \tag{2.6}$$

here, λ is the wavelength, f is the frequency, σ is the conductivity, v is the propagation velocity, and δ_{skin} is the skin depth. Values of the Table 2.3 have been acquired using representative conductivity value σ =0.01S/m which is typical for fresh water. As for sea water conductivity, σ is set to 3.2. 4.2 and 4.3S/m for the respective frequencies listed in the table [20]. First part of the table shows how the velocity increases with the increase of frequency. At 1MHz, radio signals are more than 1000 times faster than acoustic signals in sea water, which has important advantages for command latency and networking protocols where many signals have to be exchanged. The second part of table shows the impact on wavelength by increasing frequency, and highlights the degree to which a wavelength is shortened under water. For instance, at 100Hz the free space wavelength is 3000km while in sea water it is only 176m. This effect has important implications for sensing and navigation applications where the frequency required for a specified dimensional resolution is much lower than in air. The third part of the table shows the range of propagation distance with the impact of increasing frequency. Recently in [47], very low frequency (VLF) has been used and achieved 40m in transmission range for 100bps data rate. By carefully choosing the frequency and associated communication protocol, it is possible to achieve greater ranges as depicted in Table 2.3.

Table 2.3 Radio signals characteristics in underwater

		Frequencies		
		100(Hz)	1×10^3(Hz)	1×10^6(Hz)
Velocity (m/s)	Sea water	1.77×10^4	4.88×10^4	1.52×10^6
	Fresh water	3.16×10^5	1.00×10^6	3.16×10^7
	Free space	3.00×10^8	3.00×10^8	3.00×10^8
Wavelength (m)	Sea water	1.76×10^2	4.88×10^1	1.52×10^0
	Fresh water	3.16×10^3	1.00×10^3	3.16×10^3
	Free space	3.00×10^6	3.00×10^5	3.00×10^2
Propagation distance (m) for 100 dB attenuation	Sea water	3.23×10^2	8.92×10^1	2.79×10^0
	Fresh water	5.78×10^3	1.83×10^3	5.78×10^1

2.4 Sensors Localization

Localization is a method of determining the location of an entity, e.g., a node in a network or a vehicle in an automated traffic situation. Self-localization capability is a highly desirable characteristic of wireless sensor networks. In environmental monitoring applications such as bush fire surveillance, water quality monitoring and precision agriculture, the measurement data are meaningless without knowing the location where the data are obtained from. Moreover, location estimation may enable a myriad of applications such as inventory management, intrusion detection, road traffic monitoring, health monitoring, reconnaissance and surveillance [48].

Sensor network localization algorithms estimate the locations of sensors with initially unknown location information by using knowledge of the absolute positions of a few sensors and inter-sensor measurements such as distance and bearing measurements. Sensors with known location information are called anchors and their locations can be obtained by using a GPS, or by installing anchors at points with known coordinates. In applications requiring a global coordinate system, these anchors will determine the location of the sensor network in the global coordinate system. And in applications where a local coordinate system suffices (e.g., smart homes), these anchors define the local coordinate system to which all other sensors are referred. Because of constraints on the cost and size of sensors, energy consumption, implementation environment (e.g., GPS is not accessible in some environments) and the deployment of sensors (e.g., sensor nodes may be randomly scattered in the region), most sensors do not know their locations. These sensors with unknown location information are called non-anchor nodes and their coordinates are estimated by localization algorithms.

In general, localization schemes in wireless sensor networks can be classified into three categories: geometric analysis approach, proximity approach, and scene analysis approach [49]. With geometric analysis or range-based approaches, each ordinary node (node to be localized) relies on time and/or bearing information to evaluate its distance to other reference nodes (with known locations) in the system. It then utilizes multilateration/triangulation to estimate its own location. On the other hand, in proximity approaches, ordinary nodes infer their proximity to reference nodes (e.g., in terms of number of hops) so as to achieve coarse localization, e.g., in an area instead of a specific location. Lastly, scene analysis obtains localization information by analyzing 'pictures' taken by the sensor nodes and comparing the pictures with previously available 'training' data.

Although localization has been widely studied for terrestrial wireless sensor networks, existing techniques cannot be directly applied to UWSNs due to the challenges associated with such networks. Chandrasekhar et al. [50] explore such schemes for UWSNs, as well as the challenges in meeting the requirements posed by UWSNs for off shore engineering applications. Since then, a multitude of localization schemes have been proposed specifically for UWSNs. Since most underwater localization schemes are range-based, we elaborated more on range based while exploring literatures on WSN and UWSN in the following sections.

2.5 Distance Measurement Techniques

Distance measurement techniques in WSN localization can be broadly classified into three categories: distance related measurements, angle of arrival measurements and received signal strength profiling techniques. Following sections explores those techniques as well as its scopes and limitations.

2.5.1 Distance Related Measurement

Distance related measurements include propagation time based measurements, i.e., one-way and roundtrip propagation time measurements, TDoA measurements, and RSS measurements. Another interesting technique measuring distance, which does not fall into the above categories, is the lighthouse approach shown in [51]. Following paragraphs explores those, and identifies their limitations.

2.5.1.1 Time of Arrival (ToA) Measurements

Distances between neighboring sensors can be estimated from one-way or roundtrip propagation time of the signals in between beacon and sensors. One-way propagation time measurements measure the difference between the sending time of a signal at the transmitter and the receiving time of that at the receiver. It requires the local time at the transmitter and the local time at the receiver to be accurately synchronized. This requirement may add to the cost of sensors by demanding a highly accurate clock and/or increase the complexity of the sensor network by demanding a sophisticated synchronization mechanism. This disadvantage makes one-way propagation time measurements a less attractive option than measuring roundtrip time in WSNs. Roundtrip propagation time measurements measure the difference between the time when signals are sent by a sensor and the time when the signals returned by a second sensor is received at the original sensor. Since the same clock is used to compute the roundtrip propagation time, there is no synchronization problem. The major error source in roundtrip propagation time measurements is the delay required for handling the signals in the second sensor. This internal delay is either known via a priori calibration, or measured and sent to the first sensor to be subtracted.

Time delay measurement is a relatively mature field in the terrestrial localization. The most widely used method for obtaining time delay measurement is the generalized cross correlation method [52]. A recent trend in propagation time measurements is the use of ultra wide band (UWB) signals for accurate distance estimation [53, 54]. A UWB signal is a signal whose bandwidth to center-frequency ratio is larger than 0.2 or a signal with a total bandwidth of more than 500MHz. UWB can achieve higher accuracy because its bandwidth is very large and therefore its pulse has a very short duration. This feature makes fine time resolution of UWB signals and easy separation of multipath signals possible. The feasibility of using UWB signals underwater not possible due to limited propagation distance. Besides, GPS uses the same technique with collaboration of atomic clock for synchronization; it gives pretty accurate result since the tremendous speed of radio does not take long to cover the distances between the satellite and the sensors on the ground. This technique is quite impossible due to complexity in time synchronization between nodes for a short distance.

2.5.1.2 Time Difference of Arrival (TDoA) Measurements

Fig. 2.3 shows a TDoA localization scenario with a group of four receivers at locations $\boldsymbol{r}_1$, $\boldsymbol{r}_2$, $\boldsymbol{r}_3$, $\boldsymbol{r}_4$ and a transmitter at $\boldsymbol{r}_t$. The TDoA between a pair of receivers i and j is given by Eq. (2.7).

$$\Delta t_{ij} \triangleq t_i - t_j = \frac{1}{c}\left(\|\boldsymbol{r}_i - \boldsymbol{r}_t\| - \left\|\boldsymbol{r}_j - \boldsymbol{r}_t\right\|\right), \;\; i \neq j \tag{2.7}$$

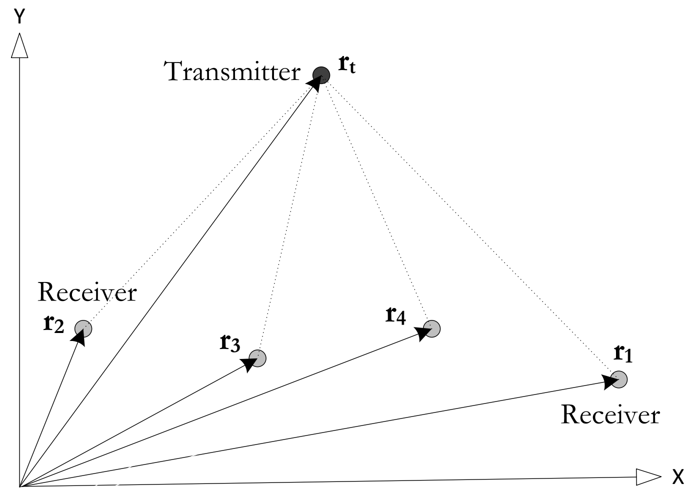

Fig. 2.3 Localization using time difference of arrival measurements

where t_i and t_j are the time when a signal is received at receivers i and j, respectively, C is the propagation speed of the signals, and $\|\ldots\|$ denotes the Euclidean norm. Measuring the TDoA of a signal at two receivers at separate locations is a relatively mature field [55]. The most widely used method is the generalized cross-correlation method, where the cross-correlation function between two signals s_i and s_j received at receivers i and j is given by integrating the lag product of two received signals for a sufficiently long time period T as in Eq. (2.8).

$$\rho_{i,j}(\tau) = \frac{1}{T}\int_0^T s_i(t)\, s_j(t-\tau)dt \tag{2.8}$$

The cross-correlation function can also be obtained from an inverse Fourier transform of the estimated frequency domain cross-spectral density function. Frequency domain processing is often preferred because the signals can be filtered prior to computation of the cross-correlation function. The cross-correlation approach requires very accurate synchronization among receivers but does not impose any requirement on the signals transmitted by the transmitter. The accuracy and temporal resolution capabilities of TDoA measurements will improve when the separation between receivers increases because this increases the difference between time-of-arrivals. Closely spaced multiple receivers may give rise to multiple received signals that cannot be separated. For example, TDoA of multiple signals that are not separated by more than the width of their cross-correlation peaks (whose location on the time-delay axis corresponds to TDoA) usually cannot be resolved by conventional TDoA measurement techniques [56]. Yet another factor affecting the accuracy of TDoA measurement is multipath. Overlapping cross-correlation peaks due to multipath often cannot be resolved. Even if distinct peaks can be resolved, a method must be designed for selecting the correct peak value, such as choosing the largest or the first peak [57]. It is worth noting that Gardner and Chen proposed an approach in [56] which exploits the cyclostationarity property of a certain signal to obtain substantial tolerance to noise and interference. The cyclostationarity property is a direct result of the underlying periodicities in the signal due to periodic sampling, scanning, modulating, multiplexing, and coding operations employed in the transmitter. Both the frequency-shifted and time-shifted cross-correlations are utilized to exploit the unique cyclostationarity property of the signal. Their method requires the signal of interest to have a known analog frequency or digital keying rate that is distinct from that of the interfering signals.

2.5.1.3 Received Signals Strength Measurements

Each ordinary node determines its distance from a reference node by measuring the received signals strength and comparing it with a range dependent signal attenuation model [58-60]. These techniques are based on a standard feature found in most wireless devices, a received signal strength indicator (RSSI). They are attractive because they require no additional hardware, and are unlikely to significantly impact local power consumption, sensor size and thus cost. However, it is difficult to achieve accurate ranging when multipath and shadow fading effects exist [13].

In free space, the RSS varies as the inverse square of the distance d between the transmitter and the receiver once all other factors are kept same. If the received power of sensors is denoted by $P_r(d)$, the received power $P_r(d)$ is related to the distance d through Eq. (2.9), the Friis equation [61].

$$P_r(d) = \frac{P_t G_t P G_r \lambda^2}{(4\pi)^2 d^2} \tag{2.9}$$

where P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain and λ is the wavelength of the transmitted signal in meters.

The free-space model however is an over-idealization, and the propagation of a signal is affected by reflection, diffraction and scattering. Of course, these effects are environment (indoors, outdoors, rain, buildings, etc.) dependent. However, it is accepted on the basis of empirical evidence that it is reasonable to model the $P_r(d)$ for any value of d at a particular location as a random and log-normally distributed random variable with a distance-dependent mean value as Eq. (2.10), as depicted in [62].

$$P_r(d)[dBm] = P_0(d_0)[dBm] - 10n_p log_{10}\left(\frac{d}{d_0}\right) + x_\sigma \tag{2.10}$$

where $P_r(d)[\mathrm{dBm}]$ is a known reference power value in dB milliwatts at a reference distance d_0 from the transmitter, n_p is the path loss exponent that measures the rate at which the RSS decreases with distance and the value of n_p depends on the specific propagation environment, x_σ is a zero mean Gaussian distributed random variable with standard deviation σ and it accounts for the random effect of shadowing [61].

It is trivial to conclude from Eq. (2.10) that, given the RSS measurement P_{ij} between a transmitter i and a receiver j, a maximum likelihood estimate of the distance, d_{ij}, between the transmitter and the receiver is

$$\hat{d}_{ij} = d_0 \left(\frac{P_{ij}}{P_0(d_0)}\right)^{1/n_p} \tag{2.11}$$

where P_{ij} and $P_0(d_0)$ are measured in milliwatts instead of dB milliwatts. Maximum likelihood estimate in Eq. (2.11) is a biased estimate of the true distance and an unbiased estimate is given by Eq. (2.12).

$$\hat{d}_{ij} = d_0 \left(\frac{P_{ij}}{P_0(d_0)}\right)^{-1/n_p} e^{-\frac{\sigma^2}{2\eta^2 n_p^2}} \tag{2.12}$$

where $\eta = \frac{10}{\ln(10)}$. Since the path loss in underwater acoustic channels is usually time varying and multipath effect can result in significant energy fading, the RSSI method is not the primary choice for underwater localization.

2.5.2 Angle of Arrival (AoA) Measurements

The angle-of-arrival measurement techniques can be further divided into two subclasses: those making use of the receiver antenna's amplitude response and those making use of the receiver antenna's phase response. Beamforming is the name given to the use of anisotropy in the reception pattern of an antenna, and it is the basis of AoA measurement techniques. The measurement unit can be of small size in comparison with the wavelength of the signals. The beam pattern of a typical anisotropic antenna is shown in Fig. 2.4. One can imagine that the beam of the receiver antenna is rotated electronically or mechanically, and the direction corresponding to the maximum signal strength is taken as the direction of the transmitter. Relevant parameters are the sensitivity of the receiver and the beam width. A technical problem to be faced and overcome arises when the transmitted signal has varying signal strength. The receiver cannot differentiate the signal strength variation due to the varying amplitude of the transmitted signal and the signal strength variation caused by the anisotropy in the reception pattern. One approach to dealing with the problem is to use a second non-rotating and omnidirectional antenna at the receiver. By normalizing the signal strength received by the rotating anisotropic antenna with respect to the signal strength received by the non-rotating omnidirectional antenna, the impact of varying signal strength can be largely removed.

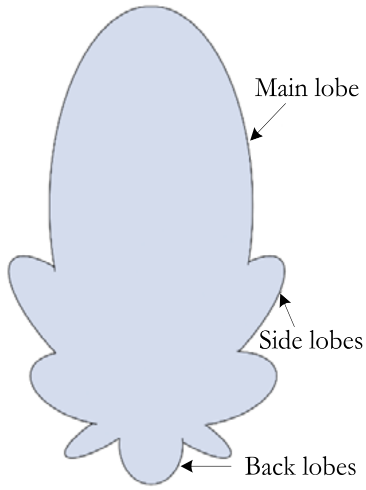

Fig. 2.4 Horizontal pattern of a typical anisotropic antenna

Another widely used approach explains in [63], where it explains to cope with the varying signal strength problem is to use a minimum of two (but typically at least four) stationary antennas with known anisotropic antenna patterns. Overlapping of these patterns and comparing the signal strength received from each antenna at the same time yields the transmitter direction, even when the signal strength changes. Coarse tuning is performed by measuring which antenna has the strongest signal, and it is followed by fine tuning which compares amplitude responses. Because small errors in measuring the received power can lead to a large AoA measurement error, a typical measurement accuracy for four antennas is $10\text{-}15^0$. This can be improved to about 5^0 and 2^0 with six and eight antennas respectively.

The second category of measurement techniques, known as phase interferometry [57] where it derives the AoA measurements from the measurements of the phase differences in the arrival of a wave front. It typically requires a large receiver antenna (relative to the wavelength of the transmitter signal) or an antenna array. Fig. 2.5 shows an antenna array of N antenna elements. The adjacent antenna elements are separated by a uniform distance d. The distance between a transmitter far away from the antenna array and the i^{th} antenna element can be approximated by

$$R_i \approx R_0 - id\cos\theta \tag{2.13}$$

where R_0 is the distance between the transmitter and the 0^{th} antenna element and θ is the bearing of the transmitter with respect to the antenna array. The transmitter signals received by adjacent antenna elements have a phase difference of $d2\pi\frac{d\cos\theta}{\lambda}$, which allows us to obtain the bearing of the transmitter from the measurement of the phase difference. This approach works quite well for high SNR but may fail in the presence of strong co-channel interference and/or multipath signals.

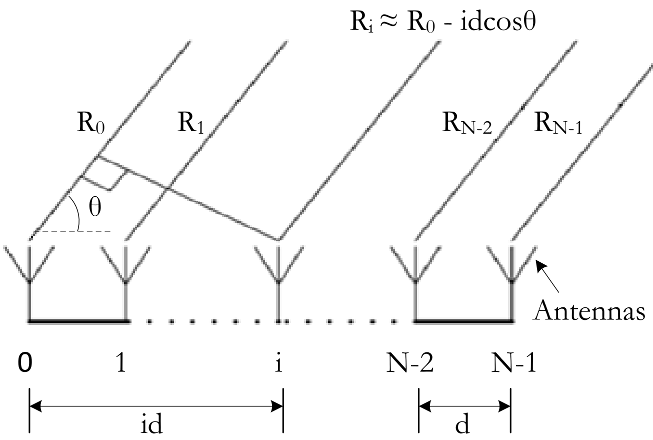

Fig. 2.5 Antenna array with N antenna elements

The accuracy of AoA measurements is limited by the directivity of the antenna, by shadowing and by multipath reflections. How to obtain accurate AoA measurements in the presence of multipath and shadowing errors has been a subject of intensive research. TDoA measurements rely on a direct LOS path from the transmitter to the receiver. However, a multipath component may appear as signals arriving from an entirely different direction and can lead to very large errors in AoA measurements. Multipath problems in AoA measurements can be addressed by using the maximum likelihood (ML) algorithms [7]. Different ML algorithms have been proposed in the literature which make different assumptions about the statistical characteristics of the incident signals [64, 65]. They can be classified into deterministic and stochastic maximum likelihood methods. Typically ML methods will estimate the AoA of each separate path in a multipath environment. The implementation of these methods is computationally intensive and requires complex multidimensional search. The dimensionality of the search is equal to the total number of paths taken by all the received signals. The problem is further complicated by the fact that the total number of paths is not known *a priori* and must be estimated. Different from the earlier ML methods, which assume the incoming signal is an unknown stochastic process, another class of ML methods assume that the structure of the signal waveform is known to the receiver [66, 67]. This assumption is possible in some digital communication systems because the modulation format is known to the receiver and many systems are equipped with a known training sequence in the preamble. This extra information is exploited to improve the accuracy of AoA measurements or simplify computation.

Another class of AoA measurement methods is based on so-called subspace-based algorithms. The most well-known methods in this category are multiple signal classification (MUSIC) [68] and estimation of signal parameters by rotational invariance techniques (ESPRIT) [69]. These eigenanalysis based direction finding algorithms utilize a vector space formulation, which takes advantage of the underlying parametric data model for the sensor array problem. They require a multi-array antenna in order to form a correlation matrix using signals received by the array. These eigenanalysis based algorithm works well in terrestrial environment but installing of multi-array of antenna in underwater environment is very difficult due to water current. Moreover, dynamic localization is quite impossible where previous infrastructure is absent.

2.5.3 Received Signal Strength (RSS) Profiling Measurement

The RSS profiling-based localization techniques are mainly performed by constructing a form of map of the signal strength behavior in the coverage area [70-72]. The map is obtained either offline by a priori measurements or online using sniffing devices [71] deployed at known locations. They have been mainly used for location estimation in wireless local area networks (WLAN), but they would appear to be attractive also for wireless sensor networks.

In this technique, in addition to anchor nodes (e.g., access points in WLANs) and non-anchor nodes, a large number of sample points (e.g., sniffing devices) are distributed throughout the coverage area of the sensor network. At each sample point, a vector of signal strengths is obtained, with the j^{th} entry corresponding to the j^{th} anchor's transmitted signal. Of course, many entries of the signal strength vector may be zero or very small, corresponding to anchor nodes at larger distances (relative to the transmission range or sensing radius) from the sample point. The collection of all these vectors provides a map of the whole region by extrapolation in the vicinity of the sample points. The collection constitutes the RSS model, and it is unique with respect to the anchor locations and the environment. The model is usually stored in a central location. By referring to the RSS model, a non-anchor node can estimate its location using the RSS measurements from anchors. RSS profiling measurement technique performs better job when the problem domain is predefined and does not change its specification so often; in case of underwater environment where the variables changes from one place to other. Besides, dynamic localization technique does not depend on previously measured specifications or infrastructure; hence this technique of measurement in localization is not suitable for underwater environment.

2.6 Localization Techniques

Localization has been widely explored for terrestrial wireless sensor networks, with many localization schemes being proposed so far. Generally speaking, these schemes can be classified into three categories: range-based, range-free and finger-printing schemes. The former covers the protocols that use absolute point-to-point distance (i.e., range) estimates or angle estimates to calculate locations, while the rest of them have no assumptions about the availability or validity of such range information. Although range-based protocols can provide more accurate position estimates, they need additional hardware for distance measures, which will increase the network cost. On the other hand, range-free schemes do not need additional hardware support, but can only provide coarse position estimates. As we are interested in accurate localization, thus range-based schemes are potentially good choice for UWSNs. Following sections elaborates different schemes, focusing mainly on range-based localization.

2.6.1 Range-based Localization

In range-based schemes, precise distance or angle measurements are made to estimate the location of nodes in the network. Range based schemes, which rely on range and/or bearing information, use Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) or Received Signal Strength Indicator (RSSI) to estimate their distances to other nodes in the system. GPS [73], and Cricket [74] are examples of schemes that use ToA or TDoA of acoustic or RF signals for localization in terrestrial sensor networks.

In the context of wireless sensor networks, range-based schemes can be divided into three categories: infrastructure-based schemes, distributed positioning schemes and schemes that use mobile beacons. Each category is discussed in detail followed by the challenges faced by this class of schemes.

2.6.1.1 Infrastructure-based Positioning Schemes

Infrastructure-based (anchor-based) localization systems are similar to the GPS scheme. The GPS space segment consists of 24 satellites in the medium earth orbit at a nominal altitude of 20,200 km with an orbital inclination of 55^0. Each satellite carries several high accuracy atomic clocks and radiates a sequence of bits that starts at a precisely known time. The location of a GPS satellite at any particular time instant is known. A GPS receiver located on the earth derives its distance from a GPS satellite from the difference of the time a GPS signal is received at the receiver and the time the GPS signal is radiated by the satellite. Ideally, distance measurements to three GPS satellites allow the GPS receiver to uniquely determine its position. In reality, four satellites, rather than three, are required because of synchronization error in the receiver's clock. The fourth distance measurement provides information from which the synchronization error of the receiver can be corrected and the receiver's clock can be synchronized to accuracy better than 100ns.

Time of Arrival Based:

Generally in a WSN, for a non-anchor node at unknown location $\widehat{\boldsymbol{x}}_t$ with noise-contaminated distance measurements $\tilde{d}_1, \cdots, \tilde{d}_N$ to N anchors at known locations $\boldsymbol{x}_t, \cdots, \boldsymbol{x}_N$, the location estimation problem can be formulated using a maximum likelihood approach as following:

$$\widehat{\boldsymbol{x}}_t = argmin\left[\boldsymbol{d}(\widehat{\boldsymbol{x}}_t) - \widetilde{\boldsymbol{d}}\right]^T \boldsymbol{S}^{-1}\left[\boldsymbol{d}(\widehat{\boldsymbol{x}}_t) - \widetilde{\boldsymbol{d}}\right] \tag{2.14}$$

where $\widetilde{\boldsymbol{d}}$ is a $N \times 1$ distance measurement vector, $\boldsymbol{d}(\widehat{\boldsymbol{x}}_t)$ is also a $N \times 1$ vector $[\|\widehat{\boldsymbol{x}}_t - \boldsymbol{x}_1\|, \dots, \|\widehat{\boldsymbol{x}}_t - \boldsymbol{x}_N\|]$ and $\boldsymbol{S}$ is the covariance matrix of the distance measurement errors. This minimization problem can be solved by conventional method.

An interesting development in the area is the use of the Cayley‑Menger determinant [75] to reduce the impact of distance measurement errors on the location estimate [76, 77]. To illustrate the concept, consider a non-anchor node $\boldsymbol{x}_t$ having distance measurements to three anchors $\boldsymbol{x}_1$, $\boldsymbol{x}_2$, $\boldsymbol{x}_3$ in $\mathcal{R}^2$ which is shown in Fig. 2.6. The Cayley‑Menger determinant of this quadrilateral is given by

$$D(\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \mathrm{x}_t) = \begin{vmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & d_{12}^2 & d_{13}^2 & d_{1t}^2 \\ 1 & d_{12}^2 & 0 & d_{23}^2 & d_{2t}^2 \\ 1 & d_{13}^2 & d_{23}^2 & 0 & d_{3t}^2 \\ 1 & d_{1t}^2 & d_{2t}^2 & d_{3t}^2 & 0 \end{vmatrix} \tag{2.15}$$

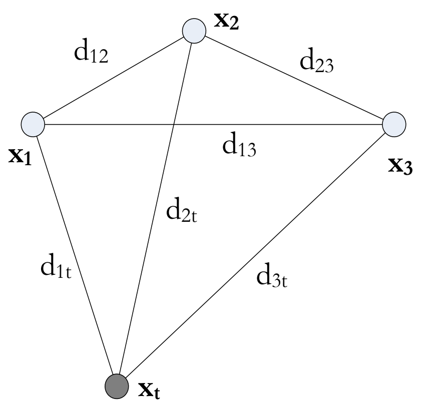

Fig. 2.6 A fully connected planar quadrilateral in sensor networks

According to the Eq. (2.15), in $\mathcal{R}^2$,

$$D(x_1, x_2, x_3, x_t) = 0 \tag{2.16}$$

The essence of using the Cayley-Menger determinant to reduce the impact of distance measurement errors is: the six edges of a planar quadrilateral are not independent; instead they must satisfy the equality constraint in Eq. (2.15). This equality constraint can be exploited to reduce the impact of distance measurement errors. This idea may also extend to TDoA and AoA based localization.

In such a system underwater anchor nodes are deployed on the sea-bed at pre-determined locations. Surface buoys, whose locations are determined by GPS, might also serve as anchor nodes. The distance to multiple anchor nodes is computed by using the propagation time of the sound signals between the sensor or the automated underwater vehicles (AUV) and the anchors. In many cases, the number of independent range measurements exceeds the number of unknown coordinates. In an over-determined system, the position estimate is made using least squares method.

Seaweb and Prospector are infrastructure based technology where seaweb was implemented by the U. S. Navy and used to track AUVs [78]. The Seaweb technology was shown to track AUVs with an accuracy of 7-9 meters, in a roughly 3×4km area. Prospector, a commercial system developed by Sonardyne, is also an infrastructure-based positioning system [79]. Four acoustic transponders are deployed on the seabed at known locations, with surface or sub-surface floats. Each transponder is deployed at a corner of a 500×500m area. The system can track divers equipped with transceivers or remotely operated vehicles (ROV) with a high degree of accuracy in water depths ranging from 5 meters to 500 meters. Sonardyne claims that it can track objects with an accuracy of 300mm, in a 500×500m grid under shallow water conditions. But the major limitation of infrastructure-based positioning schemes is that it is not dynamic as well as handy.

Large-Scale Hierarchical Localization (LSHL) approach is proposed in [80, 81] where surface buoys drift on water surface and get their locations from GPS. Anchor nodes can directly communicate with the surface buoys to get their absolute positions. Unknown nodes cannot directly communicate with the surface buoys but can communicate with anchor nodes to localize themselves. The whole localization process is divided into two sub-processes: anchor-node localization and unknown-node localization.

During the node localization process, there are two types of nodes: reference nodes and non-localized nodes. Each node (including reference nodes and non-localized nodes) periodically broadcasts a beacon message, containing its ID. All the neighboring nodes which receive this beacon message can estimate their distances to this node using measurement techniques, such as ToA. Besides, each non-localized node keeps a counter, m, of the reference nodes to which it knows the distances. Once the localization process starts, each non-localized node keeps checking m. If $m < 4$, the non-localized node broadcasts a localization message which contains all its received reference nodes' locations and its estimated distances. Besides, the non-localized node uses the 3-dimensional Euclidean distance estimation approach to estimate its distances to more non-neighboring reference nodes. After this step, the set of its known reference nodes is updated. Correspondingly, m is updated and the node returns to the m-checking procedure. Until $m \geq 4$, the non-localized node selects 4 reference nodes with the highest confidence values to localize itself. After the non-localized node is localized, it computes confidence value η. If η is larger than or equal to the confidence threshold λ, the non-localized node labels itself as a new reference node. Simulation results in [80, 81]show that localization coverage and average communication overhead are not affected much by the mobility of sensor nodes, while localization error increases noticeably with the moving speed of sensor nodes. Thus, LSHL cannot provide accurate localization accuracy in mobile UWSNs. Moreover, LSHL has inherent problem of confidence threshold λ, which can affect its performance.

Angle of Arrival Based:

In the absence of noise and interference, bearing lines from two or more receivers (anchors) will intersect to determine a unique location, i.e., the location estimate of the transmitter. In the presence of noise, more than two bearing lines will not intersect at a single point and statistical algorithms, sometimes called triangulation or fixing methods, are required in order to obtain the location estimate of the transmitter [82]. This is shown in Fig. 2.7.

Location estimation using bearing measurements is a well-researched problem. The pioneering work in the area is elaborated in [83]. The approach has been further generalized in [84, 85] and has been implemented in many practical systems. Another well-known approach is the maximum likelihood estimator where the 2D localization problem using bearing measurements can be formulated as follows.

Let $\boldsymbol{x}_t = [x_t, y_t]^T$ be the true coordinate vector of the transmitter to be estimated from bearing measurements $\beta = [\beta_1, \dots, \beta_N]^T$ where N is the total number of receivers. And let $\boldsymbol{x}_i = [x_i, y_i]^T$ be the known location of the receiver associated with the i^{th} bearing measurement.

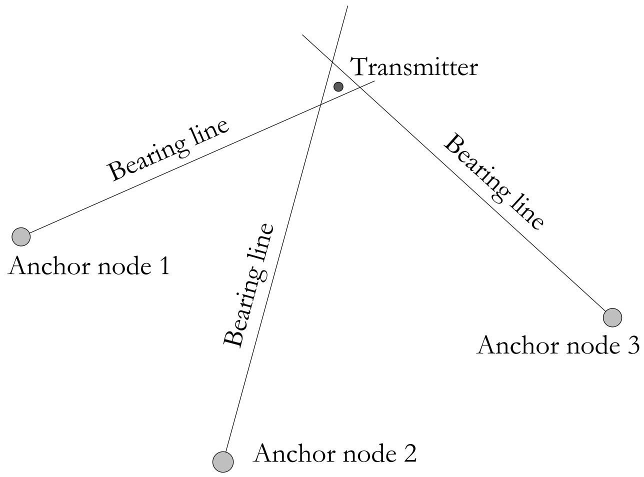

Fig. 2.7 Bearing line from three anchor nodes, with noise

The bearings of a transmitter located at $\boldsymbol{x} = [x, y]^T$ at the receiver locations is denoted by $\theta(\boldsymbol{x}) = [\theta_1(\boldsymbol{x}), \dots, \theta_N(\boldsymbol{x})]^T$, where $\theta_i(\boldsymbol{x}),\ 1 \leq i \leq N$ is related to $\boldsymbol{x}$ by

$$tan\theta_i(\boldsymbol{x}) = \frac{y - y_i}{x - x_i} \tag{2.17}$$

The measured bearings of the transmitter consist of the true bearings corrupted by additive noises $\boldsymbol{\varepsilon} = [\varepsilon_1, \dots, \varepsilon_N]^T$ which are assumed to be zero-mean Gaussian noises with $N \times N$ covariance matrices $S = diag\ \{\sigma_1^2, \dots, \sigma_N^2\}$, as in Eq. (2.18).

$$\beta = \theta(\boldsymbol{x}_t) + \varepsilon \tag{2.18}$$

When the receivers are identical and much closer to each other than to the transmitter, the variances of bearing measurement errors are equal, i.e., $\sigma_1^2 = \cdots \sigma_N^2 = \sigma^2$. The ML estimator of the transmitter location $\boldsymbol{x}_t$ is given by as following:

$$\widehat{\boldsymbol{x}}_t = \text{arg } min \frac{1}{2} [\theta(\widehat{\boldsymbol{x}}_t) - \beta]^T \boldsymbol{S}^{-1} [\theta(\widehat{\boldsymbol{x}}_t) - \beta] = \text{arg} \, min \frac{1}{2} \sum_{i=1}^{N} \frac{(\theta_i(\widehat{\boldsymbol{x}}_t) - \beta_i)^2}{\sigma_i^2} \tag{2.19}$$

The nonlinear minimization problem in Eq. 2.19 can be solved by a Newton-Gauss iteration as explained in [82].

$$\hat{x}_{t,k+1} = \hat{x}_{t,k} + \left(\theta_x(\hat{x}_{t,k})^T S^{-1} \theta_x(\hat{x}_{t,k})\right)^{-1} \theta_x(\hat{x}_{t,k})^T S^{-1} [\beta - \theta_x(\hat{x}_{t,k})] \tag{2.20}$$

where $\theta_x(\hat{\boldsymbol{x}}_{t,k})$ denotes the partial derivative of θ with respect to $\boldsymbol{x}$ evaluated at $\hat{\boldsymbol{x}}_{t,k}$. The use of Eq. (2.20) requires an initial estimate close enough to the true minimum of the cost function. Such an initial estimate may be obtained from prior information, or using a suboptimal procedure. In underwater environment, determining angle of received signal is cumbersome. Moreover, at least three anchor node needs to be installed with prior location information makes this procedure not dynamic at all.

Time Difference of Arrival Based:

Hyperbola-based Localization Scheme (HLS) is proposed in [86] where time difference of signals arrival has been utilized. Instead of using the commonly adopted circle-based detection and least squares algorithm based location estimation, the proposed scheme utilizes the hyperbola-based approach for localization and a normal distribution for estimation error modelling and calibration. When any unknown node detects one event, it will report the event to anchor nodes immediately. Anchor nodes $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ in Fig. 2.8 receive the event at time t_1 and t_2. The difference between t_1 and t_2 is a constant, in other words, the difference between the corresponding distance d_1 and d_2 is a constant. Based on the property of hyperbola, the unknown node is localized on a hyperbola N_{12}. Similarly, another hyperbola N_{23} is plotted in the same figure. More curves can be added when more anchor nodes are involved in localization. The intersection of any two curves gives an estimated position of unknown node. In practical applications, the obtained set of intersection points may not coincide or converge well. In this case, algorithms like least squares can be adopted to further improve localization accuracy.

Compared with the circle-based approach, HLS is more robust against distance measurement error and can localize more unknown nodes. Since two hyperbolas always intersect with each other with one cross point, while two circles are likely to intersect with either two or zero cross point(s); there is very little chance to have only one cross point. Simulation results show that localization accuracy of HLS is better than that of the least squares algorithm. In general, HLS is more suitable for accurate localization in UWSNs. However, in HLS, sensor nodes are required to send long-range signals, around 1,000 meters. Thus, excessive energy is consumed. Furthermore, anchor nodes need to be stationary and hence HLS is not extendable to mobile UWSNs.

Given the TDoA measurement Δt_{ij} and the coordinates of receivers i and j, Eq. (2.7) defines one branch of a hyperbola whose foci are at the locations of receivers i and j and on which the transmitter $\boldsymbol{r_t}$ must lie. In $\mathcal{R}^2$, measurements from a minimum of three receivers are required to uniquely determine the location of the transmitter as illustrated in Fig. 2.8.

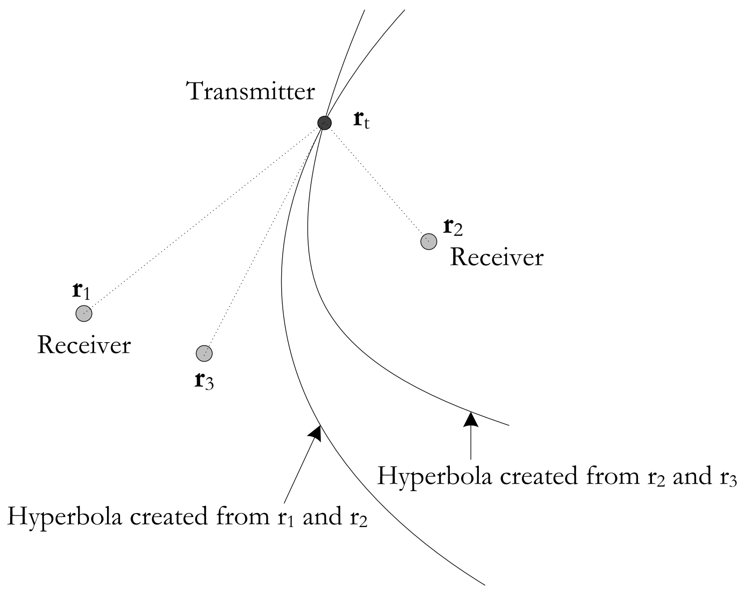

Fig. 2.8 Intersecting hyperbolas from three receivers

In a system of N receivers, there are N-1 linearly independent TDoA equations, which can be written compactly as

$$\begin{bmatrix} \|\boldsymbol{r}_1 - \boldsymbol{r}_t\| - \|\boldsymbol{r}_N - \boldsymbol{r}_t\| - c\Delta t_{1N} \\ \vdots \\ \vdots \\ \|\boldsymbol{r}_{\mathrm{N}-1} - \boldsymbol{r}_t\| - \|\boldsymbol{r}_N - \boldsymbol{r}_t\| - c\Delta t_{N-1,N} \end{bmatrix} = 0 \tag{2.21}$$

In practice Δt_{ij} is not available; instead we have the noisy TDoA measurement $\Delta \tilde{t}_{ij}$ given by

$$\Delta\tilde{t}_{ij} = \Delta t_{ij} + n_{ij} \tag{2.22}$$

where n_{ij} denotes an additive noise, which is usually assumed to be an independent zero-mean Gaussian distributed random variable. Eq. (2.21) is a nonlinear equation that is difficult to solve, especially when the receivers are arranged in an arbitrary fashion. This method relies on a good initial guess of the transmitter location. Moreover, in some situations this method can result in significant location estimation errors due to geometric dilution of precision (GDOP) effects. GDOP describes a situation in which a relatively small ranging error can result in a large location estimation error because the transmitter is located on a portion of the hyperbola far away from both receivers [87]. In [88], an exact solution to the hyperbolic equations in Eq. (2.21) is given when the number of TDoA measurements are equal to the number of unknown transmitter coordinates. However his solution cannot make use of extra measurements. Other techniques that can deal with the more general situation with extra measurements include the spherical interpolation method [89], which is derived from least-squares equation-error minimization, and the divide and conquer method [90]. The divide and conquer estimate is formed by combining the maximum likelihood estimates using possibly overlapping subsections of the measurement data vector. The divide and conquer method can achieve the optimum performance but it requires that the Fisher information matrix is sufficiently large. Chan and Ho [91] developed a closed form solution valid for an arbitrary number of TDoA measurements and arbitrarily distributed transmitters. The solution is an approximation of the maximum likelihood estimator when the TDoA measurement errors are small. This method performs significantly better than the spherical interpolation method and is more robust against noise than the ‘divide and conquer’ method. The computational complexity of Chan’s method is comparable to the spherical interpolation method but substantially less than the Taylor-series method.

Another closed form method has been developed for localization of distant transmitters based on triangulation of hyperbolic asymptotes in [92]. The hyperbolic curves are approximated by linear asymptotes. The solution exhibits some performance degradation with respect to the maximum likelihood estimator at low noise levels but outperforms the maximum likelihood estimator at medium to high noise levels. All the above methods require communication between multiple anchor nodes those act as receivers to localize single transmitter.

Asymmetrical Round Trip based Localization (ARTL) algorithm is proposed in [93]. ARTL assumes that anchor nodes can receive their own packets while unknown nodes cannot. First, the basic ranging scheme is implemented to get distances between anchor nodes and unknown nodes. As shown in Fig. 2.9, unlike existing symmetrical round-trip schemes [94], the ranging scheme here is asymmetric; that is, to estimate the distance between an anchor node and unknown node U, the initiator (the anchor node that starts the ranging task) A_i first broadcasts a ranging packet, which is received by both itself and U, as well as other non-initiator nodes A_u. Then after an arbitrary period, U responds an ACK to A_i. This ACK will not be received by U itself, but only received by A_i as well as A_u. Based on the time difference of arrival signals, the distance can be calculated. Together with collected data information, the calculated distances are sent to the base station which launches localization task. Thus, no time synchronization is required in the entire process and no complex computations are handled by anchor nodes and unknown nodes. Moreover, ARTL does not require unknown nodes to immediately reply after receiving the ranging broadcast, so U can respond ACK whenever it is convenient.

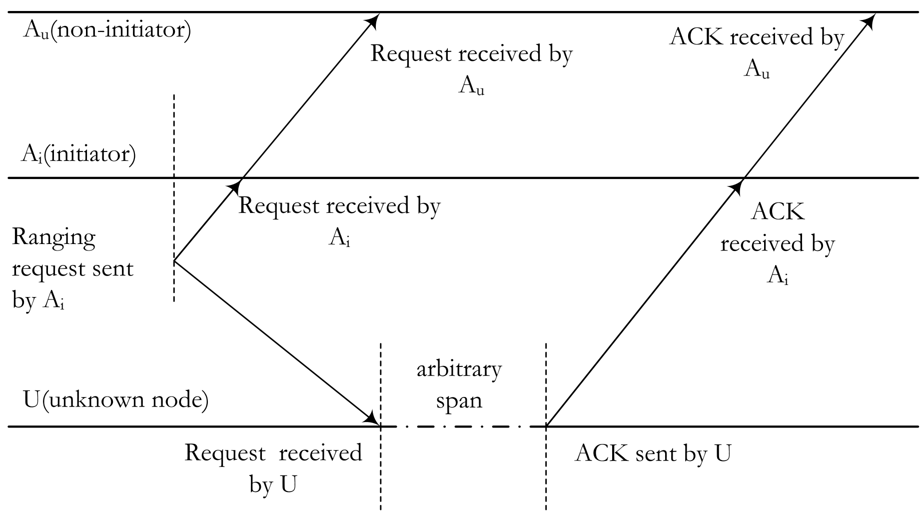

Fig. 2.9 Asymmetric round-trip localization scheme

Underwater Positioning Scheme (UPS) is proposed in [95, 96] which consists of two steps. The first step is to detect the time differences of arrival signals. Then, the time differences are transformed into range differences. As illustrated in Fig. 2.10, A is the master anchor node, which initiates a beacon signal every T seconds.

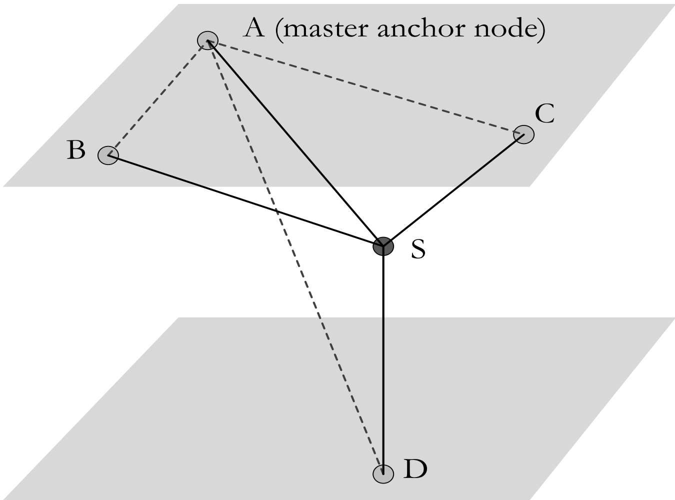

Fig. 2.10 An example of underwater positioning scheme (UPS)

B's transmission starts after it receives A's beacon signal. C's transmissions start after it receives beacon signals of both A and B. In addition, D's transmission starts after it receives beacon signals of A, B and C. After S get all the beacon signals, the time difference of arrival signals is calculated and converted to range difference. In the second step, trilateration is performed to localize unknown nodes.

UPS requires no time synchronization and has low computation overhead. As evidenced by simulation results, UPS has low localization error. It is applicable to both localization and navigation in UWSNs. Moreover, few anchor nodes are needed to perform 3D localization. However, sensor nodes outside the four anchor nodes' communication range cannot be localized. In addition, UPS does not take into account the impact of transmission failures, which is highly likely because underwater acoustic channels are unreliable. If anchor node B cannot receive the beacon signal of the master anchor node A, it will not send its own beacon signal. Then, C and D will refrain from sending as these will wait until the beacon signal from node B is received. Therefore, in [97], an Enhanced-UPS (E-UPS) is proposed where a time-out value is designed for the maximum waiting time of the anchor node messages. On the other hand, to overcome the limitation of relying on four anchor nodes, E-UPS is extended to use all anchor nodes. It is observed that up to

16% of the network containing anchor nodes is not localizable; therefore a wide coverage positioning system (WPS) is proposed to address this limitation in [98].

Localization Scheme for Large Scale (LSLS) underwater network is a scheme where UPS and USP are integrated and proposed in [99], where any localized node can work as reference node to further localize neighbor nodes. Similar to rreactive localization algorithm (RLA) and LSHL, LSLS is a hierarchical localization approach. LSLS includes three phases: sea surface anchor localization, iterative localization, and the complementary phase. In the first phase, three surface anchor nodes send their beacon messages sequentially to calculate the range difference as described in UPS. Then, unknown nodes are localized as described in USP. In the second phase, certain localized nodes are selected to serve as reference nodes. More unknown nodes are localized as described in the first phase. If a node fails to be localized in the first two phases, it can initiate a location request in the third phase. A new group of reference nodes are then selected to localize the unlocalized node.

Similar operations in the first two phases are applied in [100] without considering the remaining unlocalized nodes. Compared with UPS, LSLS can localize a large-scale UWSN with short-range acoustic communication. Moreover, LSLS localize more unknown nodes than USP does. However, more energy and communication overhead are consumed to implement the three phases localization.

2.6.1.2 Distributed Positioning Schemes

Distributed positioning schemes are employed in cases where a positioning infrastructure is not available, i.e. anchor-free. In distributed positioning schemes, nodes are able to communicate only with their one-hop neighbors and compute the distances to their one-hop neighbors. Multilateration techniques, which encompass atomic, collaborative and iterative multilateration, are then used in a distributed manner to estimate the location of each sensor node. Distributed positioning algorithms generally have three positioning phases: the distance estimation phase, where nodes estimate the distances to their neighbors, the position estimation phase, where a system of linear equations is generally solved using a least squares approach to estimate the position of the node, and finally a refinement phase, where the accuracy of the algorithm is improved by using an iterative algorithm. The NHop multilateration scheme, the hop-TERRAIN and refinement Scheme, ad hoc localization system (AHLoS), and Euclidian propagation schemes [101] fall under this category.

The N-Hop multilateration scheme [102] discusses the requirements for location solution uniqueness in the one-hop, two-hop and n-hop case. In this scheme, initial estimates for all nodes are made using the conditions of position uniqueness, and the constraints obtained from distance measurements to neighboring nodes. A refinement process is then carried out using Kalman filters. In [103], initial estimates are obtained using an algorithm similar to the range-free DV-Hop scheme. Then, a least squares method is used to refine nodes' locations based on local computations. The AHLoS scheme [104] uses iterative multilateration where unknown nodes, which estimate their locations by triangulation, become beacon nodes. The problem with such a scheme is that the error propagates through the network as the number of hops from the anchor node increases.

In distributed positioning schemes, nodes estimate their distances to neighbors by making RSSI or ToA measurements. RSSI based schemes can only provide a ranging accuracy of a few meters, while ToA based schemes can achieve ranging accuracy of a few centimeters. In underwater sensor networks, RSSI is not suitable for a dynamic problem domain; whereas, ToA based ranging is the preferred option as acoustics is the mode of communication between nodes.

Distributed positioning algorithms generally assume anchor nodes to be randomly distributed throughout the network, and the percentage of anchor nodes in the network to be quite high too, which is 5- 20% as in [102]. In terrestrial sensor networks, deploying anchor nodes is not a challenge, as nodes equipped with GPS could act as anchor nodes. However, in the case of underwater sensor networks, setting up a backbone of randomly distributed anchor nodes, whose precise locations are known, is not a trivial problem.

Under distributed positioning schemes, not all the nodes in the system are localized, even though the network might be fully connected. For example, the nodes which do not satisfy the position uniqueness conditions might not be able to compute their locations.

2.6.1.3 Schemes with Mobile Beacons

Traditional range-based schemes have fixed anchor nodes whose locations are known. Schemes have been proposed which use mobile beacons whose locations are always known [105]. In this scheme, a mobile beacon traverses the sensor network while broadcasting beacon packets which contain the location coordinates of the beacon. Any node receiving the beacon packet will be able to infer that it must be somewhere near the mobile beacon with a certain probability. RSSI measurements of the received beacon packets are used for ranging purposes. After a number of packets have been received from the mobile beacon, Bayesian inference is used to determine the location of the node. In terrestrial networks, an autonomous vehicle installed with GPS could traverse the network and broadcast beacon packets. The challenge faced by an underwater network is that the location of the AUV itself might be unknown. The location of the AUV would have to be determined first using other means before it could be used for positioning nodes on the seabed.

A scheme that uses RSSI has to deal with problems caused by large variances in reading, multi-path fading, irregular signal propagation patterns and background interference. Such schemes may not be useful in the underwater scenario due to the large variances in RSSI. Alternatively, in the underwater domain, the ToA of the acoustic signals from the mobile beacon could be used for ranging purposes.

Commercial positioning solutions as mentioned in section 2.6.1 have been developed by Sonardyne for shallow and deep water applications where a ship equipped with GPS suspends a transponder into the water. The sensor nodes dropped on the seabed are also equipped with acoustic transponders. The position of a node on the seabed is then calibrated by sailing the vessel over the area in which the nodes are dropped. In [106] this scheme has been shown to work well in shallow waters. It has also been claimed that the nodes on the seabed are localized with an accuracy of within one meter, for water depths up to 500m. The acoustic range and bearing data from the moving ship is used to localize the nodes. In this case, the ship serves as a mobile anchor and the localization process is typically carried out in less than 20 minutes which is the biggest drawback of the scheme.

A three-Dimensional Underwater Localization (3DUL) is introduced in [107] where three buoys floating on the surface and many underwater sensor nodes are deployed at different depths. In addition, there are propelled autonomous robots freely floating with water currents. In this scheme, the underwater sensor nodes and the propelled robots are unknown nodes.

3DUL is a two phase protocol. During the first phase, unknown nodes estimates the distances to their neighboring buoys by using two-way message exchange technique and acquires their depth information. This phase of the algorithm is called ‘ranging’. Once the distances to at least three buoys are estimated, the second phase of the algorithm -

'projection and dynamic trilateration' is initiated. During this phase, the unknown node projects the buoys' positions onto its horizontal level. Then, it localizes itself through trilateration and labels itself as a reference node. 3DUL does not require time synchronization. The biggest drawback of 3DUL is the very long localization time and requires four reference nodes; of which three are in known locations and one propelled autonomous robot with unknown location. Besides, ranging method requires two-message exchange technique with presumed acoustic speed which will produce enormous error in distance determination. Moreover non-linear dynamic trilateration method is used which will not guarantee a solution. These overhead of computational complexity of this scheme is huge and not feasible for a dynamic environment where localization is needed on the fly.

2.6.1.4 Schemes without Reference Point

The fourth class of schemes is different from the first three in that it does not require anchor nodes or beacon signals. In [108], a central server models the network as a series of equations representing proximity constraints between nodes, and then uses sophisticated optimization techniques to estimate the location of every node in the network.

2.6.2 Range-free Localization

Range-free localization schemes do not use range or bearing information; that is, they do not make use of any of the techniques mentioned above (ToA, TDoA and AoA) to estimate distances to other nodes. The accuracy of range-based localization depends on the accuracy of range measurement, which could suffer from errors due to nodes mobility as well as harsh underwater acoustic propagation environment. Hence, range-free schemes have been proposed that do not rely on range measurement for localization. It is worth noting, range free schemes only provide a coarse estimate of a node's location. Followings are few range-free localization schemes explored for possible potentiality in UWSNs.

2.6.2.1 Hopcount Based Schemes

Distance Vector Hop (DV-Hop) is one of the most basic range-free schemes, and it first employs a classical distance vector exchange so that all nodes in the network get distances in number of hops to the anchor nodes. Each node maintains a table and exchanges updates only with its neighbors. Once a landmark i.e. an anchor gets distances to other landmarks, it estimates an average distance for one hop, which is then propagated as a correction to the entire network. Upon receiving the correction, an arbitrary node then estimates its distances to the landmarks, in meters, which can be used to perform triangulation [109]. The DV-Hop algorithm performs well only in networks that have uniform and dense node distributions.

Density-aware Hop-count Localization (DHL) schemes is proposed in [110] where the node distribution is more likely to be non-uniform and sparse in certain regions for actual deployments; it improves the accuracy of location estimation when the node distribution in the network is not uniform. This scheme takes into account both the density of a node's neighborhood when computing the average hop distance, as well as, the fact that error in distance estimation tends to accumulate with the increase of path length.

Iterative multilateration, the process where unknown nodes which have estimated their locations become anchor nodes, must be carefully employed in range-free hopcount based schemes. For example, in a network with anchor nodes placed at the corners of a square grid, it is observed that the error is higher along the boundaries and lower in the middle of the region. Based on this observation, a selective iterative multilateration (SIM) algorithm [111] is proposed where new anchor nodes are selected judiciously such that their initial position estimates are sufficiently accurate.

2.6.2.2 Centroid Based Scheme

In this scheme, anchor nodes are placed to form a rectangular mesh. The anchor nodes send out beacon signals at periodic intervals with their respective locations. From the beacon signals received, a receiver node infers proximity to a collection of anchor nodes. The location of the node is then estimated to be the centroid of the anchor nodes that it can receive beacon packets from. A high concentration of anchor nodes is required for this scheme to work well. Also, such a scheme would be hard to implement in the underwater context as it would require setting up a rectangular mesh of anchor nodes on the seabed.

2.6.2.3 Area Based Schemes

Area-based Localization Schemes (ALS) is a 2D area localization scheme is proposed by Chandrasekhar and Seah in [112] to estimate a node's position of every unknown node within a certain area rather than its exact location. The main responsibility of anchor nodes is to send out signals with different levels of power to localize unknown nodes. Unknown nodes simply listen to the signals and record the anchor nodes' IDs and their corresponding power levels. Together with collected data, the recorded information is sent to sink node. Here, the sink node is assumed to know the positions of all anchor nodes and their respective transmitted power levels. Therefore, with proper signal propagation algorithms, sink node is able to draw out the map of areas divided by all the anchor nodes' transmitting signals, from which sink node can localize unknown nodes.

The advantages of ALS are being range-free and having no synchronization requirement. Moreover, all complex calculations are handled by the powerful sink node instead of unknown nodes. This reduces energy consumption of unknown nodes and extends the lifetime of network. Localization coverage can be appropriately broadened by adjusting the transmitting power of anchor nodes. However, as a coarse localization scheme, ALS is not convenient for applications that require accurate and instant location information. In addition, it also incurs high communication overhead and energy consumption. It handles localization by assuming that sink node knows the positions of all anchor nodes and their respective transmitted power levels. This assumption reduces flexibility of the network. Besides, after deploying the network, it is not possible to change positions of anchor nodes. Therefore, if the positions of anchor nodes are changed by water currents, the performance of ALS decreases greatly.

The propagation of acoustic underwater signals is subject to losses due to spreading, absorption, dispersion, multipath fading and Doppler effects. Assuming a spherical attenuation model, and neglecting losses due to multipath fading and Doppler effects, when each reference node transmits at power P_i, an ordinary node can receive the transmission as long as it falls within a circular region centered at the reference node whose radius $r(P_i)$ depends on the transmission power. Hence, by deploying several reference nodes that transmit beacons at multiple power levels, the plane is divided into many small sub-regions defined by intersecting circles. Each ordinary node listens and reports the ID and minimum transmit power at which it received the respective node's beacon to a central sink, which can then estimate its location as illustrated in Fig. 2.11. Due to limitations highlighted above, ALS is not good option for localization in UWSNs.

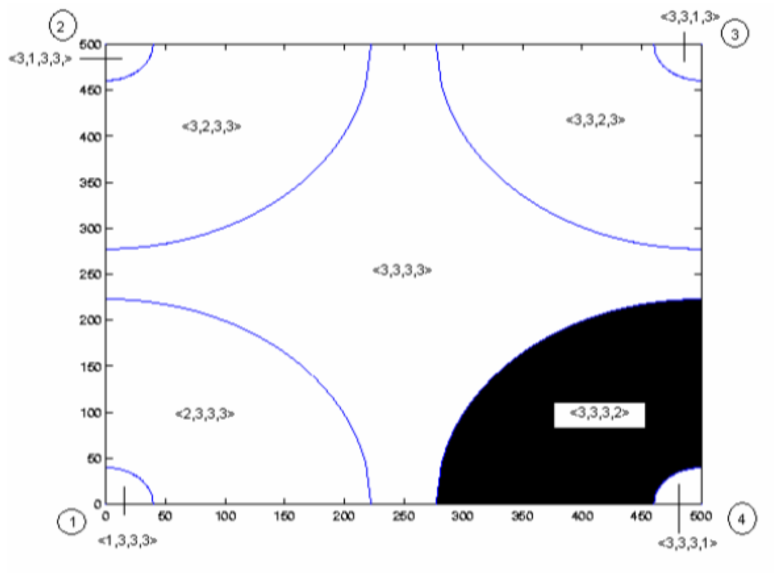

Fig. 2.11 An example of area based scheme (ALS)

3D Multistage Area Localization Scheme (3D-MALS) is proposed by Zhou et al. in [113], that combines the concepts of ALS and LSL-DET. It considers a hierarchical network architecture that comprises surface buoys with 'detachable elevator transceivers' (DET), ordinary nodes and sink nodes, and extends ALS to 3D. DET is mainly composed of an elevator and an multi-power level acoustic transceiver. The elevator helps the DET rise or dive in vertical underwater, and the transceiver communicates with unknown nodes. The DET gets coordinate from its buoy when it moves to water surface, then moves down to broadcast position information at some pre-configured depths. At every broadcast position, the DET transmits beacon signals at varying power level as described in [112, 114]. Unknown nodes listen to beacon signals periodically transmitted from the mobile DET.

To save energy consumption of unknown nodes, all the measured position information are sent to the sink node to compute the estimation areas. However, the localization accuracy of 3D-MALS is low like that of ALS. Much energy is needed to transmit multi-power level signals. Moreover, localization time depends heavily on the velocity and message sending intervals of the DET. Simulation results demonstrate its performance gain over ALS in terms of localization accuracy. However, as with ASL, it is a model-based centralized scheme that provides coarse localization.

Maximum-Likelihood Source Localization (MLSL) approach is proposed in [115] where UWSN consists of arrays of sensors. Each sensor array is equipped with an array of sensor nodes that are attached to the sensor array via wired connections. Each target waiting to be localized periodically emits a narrow-band acoustic signal. For each sensor array, using the negative log-likelihood function, sensor nodes which have received the signal can obtain the target locations and signal amplitudes. The maximum likelihood estimate of the target location is obtained based on the global likelihood function, which is the sum of the local likelihood functions.

MLSL approach does not need distance measurement and time synchronization. Computation overhead of sensor nodes and targets are low, while communication overhead and energy consumption are high as all the local likelihood functions are forwarded to a fusion center. Moreover, the local wired and global wireless network architecture is not feasible for large scale UWSNs.

Reactive Localization Algorithm (RLA) is proposed in [116]. Instead of localizing every single node in the network, RLA localizes a node that detects an event. Once a sensor node detects an event, RLA which consists of two steps starts. The first step is to find anchor nodes where the sensor node first broadcasts a hello message with its ID and energy level to its neighbors. By the K-node coverage algorithm, at least 4 non-coplanar anchor nodes are found. The second step is reactive localization of the sensor node. Once the selected anchor nodes receive localization request message, they reply with their location information. The sensor node hence localizes itself by quadrilateration. Due to additional process for anchor nodes' localization, energy consumption and communication overhead of RLA are high. Furthermore, accumulated localization error exists in calculated positions of the sensors.

2.6.2.4 Mobile Beaconing Based Schemes

While the above schemes rely on static references, Luo et al in [117, 118] proposed a 2D and 3D underwater localization scheme using a single AUV with directional beacons to localize stationary nodes. Using directional beaconing such as: UDB–2D and localization with directional beaconing (LDB–3D) scheme both has an AUV traverses a preprogramed route and performs directional (vertical) beaconing periodically. The scheme assumes that the AUV moves with constant and known speed and knows its position underwater accurately using integrated GPS and integrated network system (INS), and that the vertical channel used in UDB is characterized by little or no time dispersion. Fig. 2.12 gives an illustration of how ordinary sensor node, equipped with a pressure sensor, localizes itself with LDB.

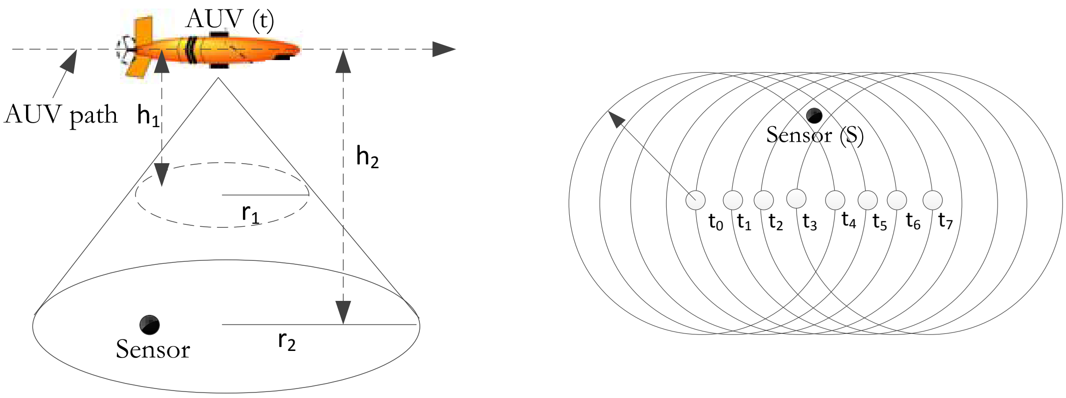

Fig. 2.12 Localization with directional beaconing (LDB)

Assuming a beamwidth of α, the radius of the circle formed by the intersection of the beam with the horizontal plane for which S resides, r_2 is given as

$$r_2 = \tan\left(\frac{\alpha}{2}\right) \times h_2 \tag{2.23}$$

where h_2 is the difference in depth between the AUV and node S. Assuming that the AUV traverses a straight line path and broadcasts its own location periodically, at times $t_0, t_1, \dots, t_n$ at instant t_i, node S would record the AUV's coordinates (x_i, y_i), if it can hear them, i.e., if it lies within the circle of radius r_2 centered at (x_i, y_i). According to Fig. 2.12, sensor node S first hears the AUV's beacons when it transmits at (x_i, y_i) at time t_1 and last hears them when it transmits at (x_i, y_i) at time t_5. Accordingly, it estimates its position, $(\tilde{x}_i, \tilde{y}_i)$ as follows

$$\tilde{x} = \frac{x_1 + x_2}{2} \tag{2.24}$$

$$\tilde{y} = y_1 + \frac{\sqrt{r_2^2 - \frac{x_5 - x_1 + 2d^2}{2}} + \sqrt{r_2^2 - \frac{x_5 - x_1^2}{2}}}{2} \tag{2.25}$$

where d is the distance traversed by the AUV between successive beaconing instances. This technique is one of the earliest to introduce the idea of using directional beacons to localize unknown nodes in UWSNs that uses angle information to localize unknown nodes. However, localization coverage is limited, hence, UDB is not suitable for large scale UWSN. Moreover, if the AUV sends beacons with too long intervals, many unknown nodes may not be localized.

Range-free Scheme Based on Mobile Beacons (RSMB) is proposed in [119] where a mobile anchor node moves on the sea surface at a constant speed and broadcasts beacons at regular intervals, called beacon distance d. Here, the mobile anchor node follows the random way-point (RWP) model [120]; the mobile anchor node moves in a series of straight paths to random destinations. Unknown nodes are installed with pressure sensors to obtain depth information. As shown in Fig. 2.13, the unknown node can receive five beacons from the mobile anchor node. Since the unknown node knows its own depth information, the received beacons can be projected on the plane where it locates. RSMB consists of two steps. The first step is to select three beacons among the received beacons. The second step is to estimate the location of unknown node.

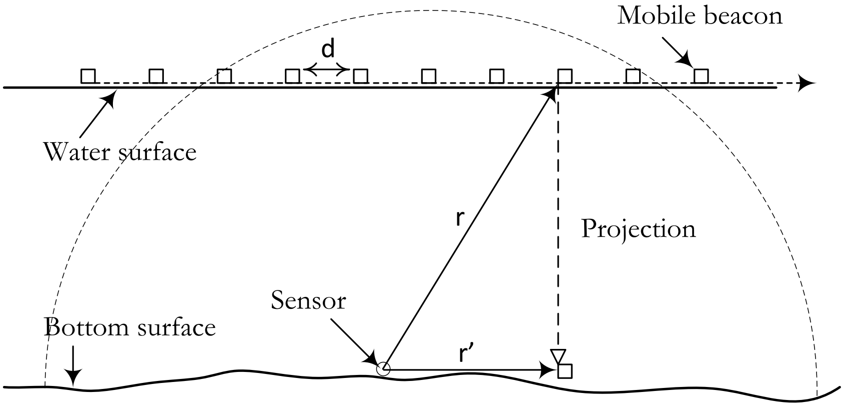

Fig. 2.13 Range free scheme based on mobile beacons (RSMB)

In RSMB, each unknown node can estimate its own location independently. However, there are some problems of RSMB. Firstly, localization time and accuracy mainly depend on the beacons' sending interval. Secondly, high energy is consumed for the anchor node's movement and the projection technology. Thirdly, it cannot localize unknown nodes in deep water. Furthermore, the path planning of the mobile anchor node, which severely affects localization accuracy is not determined.

2.6.3 Mobile Localization

Mobile localization is mainly focused on localizing mobile nodes with stationary and mobile reference points. It requires more reference nodes and sometimes significant infrastructure to keep track of the mobile deployed nodes. Multiple schemes are proposed in different categories as follows:

2.6.3.1 Centralized Localization

Absolute Positioning Scheme (APS) is proposed to localize an AUV in [121]; AUVs provide researchers with new forms of access to ocean which requires AUVs' accurate position information. As shown in Fig. 2.14, an AUV transmits an interrogation pulse at a fixed rate. The signals received at the surface consist of a direct signal from the AUV and a reply from each of the transponders. The time difference of arrivals along with depth measurements from an on board pressure sensor are used to localize the AUV.

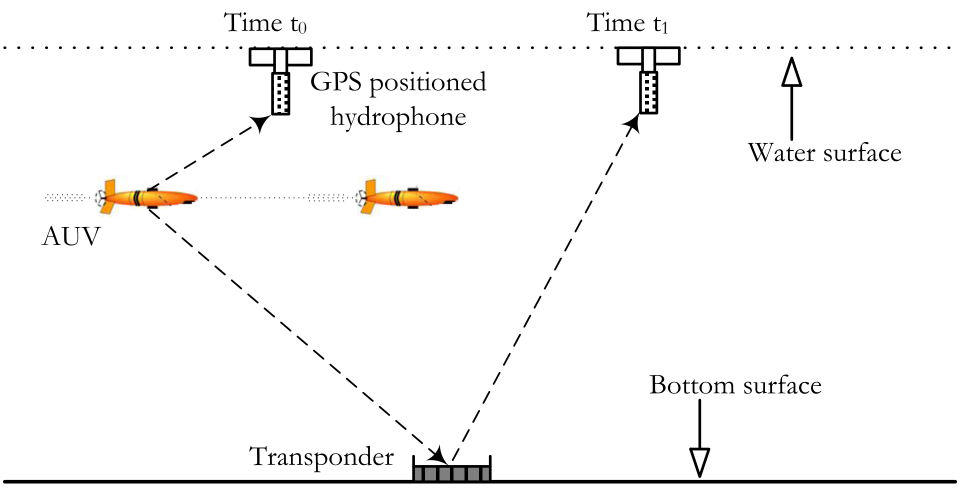

Fig. 2.14 An example of absolute positioning scheme (APS)

APS is proposed to localize one AUV and localization coverage is limited by the acoustic interrogation pulse. Both the AUV and the ship with hydrophones are moving, so the time difference of signal arrivals is not accurate enough. Furthermore, using the GPS-positioned hydrophone aboard the ship to localize AUV incurs high hardware cost and high energy consumption. Therefore, another AUV localization system is proposed in [122], namely particle filter [123] based localization system (PFLS). PFLS is implemented on board, the AUV to localize itself in real-time using ranging information obtained from an UWSN. The AUV is equipped with an acoustic modem allowing it to communicate with the surrounding sensor nodes. Based on the round trip time, the AUV can determine its distances to neighbor nodes. Compared with APS, PFLS are much more efficient.

Energy-Efficient Ranging Scheme (EERS) is proposed in [124] to localize a swarm of sensor-equipped drifters that float freely with ocean currents. In stationary UWSNs, unknown nodes communicate with anchor nodes to estimate the distances between them, from which their positions can be deduced. However, in mobile UWSNs, because of sensor nodes' uncontrollable mobility, it is impractical to assume that unknown nodes are always in the communication range of fixed anchor nodes.

In this method, firstly, range can be deduced from the one-way time of exchange message arrival measurement. This step is called sufficient distance map estimation (SDME). SDME consists of a synchronization step (SDME-S), followed by a distance estimation step (SDME-D). SDME-S is a synchronization-data collection algorithm to achieve time synchronization. SDME-D is a two-step distance estimation process. During distance estimation, not all the nodes need to broadcast localization message. Therefore, SDME-D first selects the subset nodes that need to broadcast localization message. The localization based on EERS is an anchor-free self-localization scheme, which can be extended for large scale UWSNs. Although time synchronization is required to handle the one-way ToA, SDME-S can tackle the time synchronization problem efficiently. SDME does not need to be 'a full localization' scheme. While submerged, the drifters only need to collect distance estimates. The positions can be calculated after the mission is over. Therefore, energy consumption for position calculation can be saved and complex computation is avoided. However, the subset nodes selection requires a single broadcast per node, which consumes huge energy and prolongs localization time.

Motion-Aware Self-Localization (MASL) is another scheme to localize mobile node. In wireless communication process, in order to avoid excessive collisions occurring over a shared channel, the gathering of ranging information actually occurs over a short time epoch *T*. The problem is that mobility causes the node positions to change significantly during epoch *T*. Therefore, in [125], the authors proposed a motion-aware self-localization scheme for mobile UWSNs. During MASL, nodes first perform ranging with their neighbors to get all the distance estimates in the localization epoch. Then, all distance estimates are sent to a central station and processed offline. An iteration algorithm is started to obtain the positions. The algorithm refines position distributions by dividing the area of operation into smaller grids in every phase, selecting the area in which the node resides with high probability and using it in the next iteration.

MASL is a centralized anchor-free localization algorithm, which reduces unknown nodes' computational burden and can be used to localize large scale UWSNs. The problem of MASL is that the iterative algorithm cannot provide real-time location information. Real applications always need UWSNs to do online monitoring and provide real-time location information. Simulation results show that, compared with a robust self-localization algorithm, named multi-dimensional scaling (MDS) [126], MASL localizes 70% of nodes with error lower than that of MDS.

Collaborative Localization Scheme (CLS) for mobile UWSNs is proposed in [127], where nodes collaborate to determine their positions autonomously without using long range transponders on surface buoys or ships. Starting at the surface where the network is deployed, sensor nodes use buoyancy control to descend deeper into ocean. Once a maximum desired depth is reached, they travel back to the surface. While nodes are descending, although they know their depth by pressure sensors, their positions in the other two dimensions change continuously due to the motion induced by currents. In order to track the descending nodes, they are classified into two categories: profilers and followers. Initially, all nodes are at the surface, so that their positions can be obtained by GPS. A profiler travels to a depth first. Then, followers travel the trajectory of the profiler. All the nodes descend with the same speed. The profiler's location is a prediction of the followers' future locations by AoA technique as shown in Fig. 2.15.

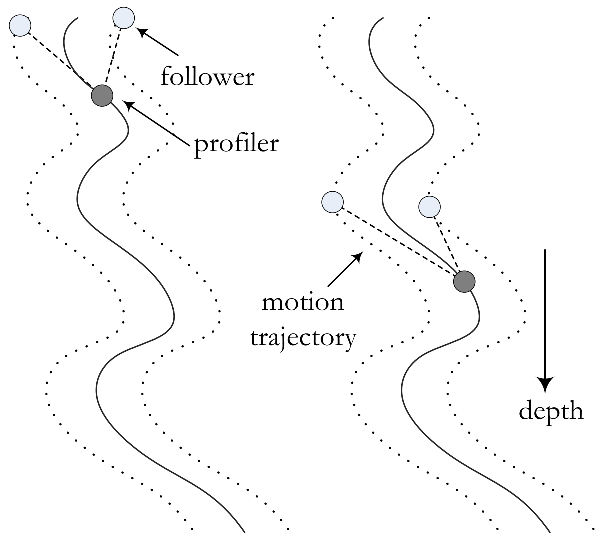

Fig. 2.15 An example of collaborative localization scheme (CLS)

CLS is an anchor-free and cost effective self-localization strategy that does not require prior node planning. The drawback of CLS is its architectural dependence; for a sparse or non-homogenous network, the performance of CLS can be affected significantly. Moreover, time synchronization is required. In order to get higher localization accuracy, the profilers have to stay closer to the followers. Otherwise, the profilers going out of communication range of the followers results in localization failures.

Three-Dimensional Underwater Target Tracking (3DUT) scheme is proposed in [128]. As shown in Fig. 2.16, at least three anchor nodes float at the surface of water. One of these nodes is the sink (node *A*) which collects the information from underwater sensor nodes and carries out the calculations. The black nodes collect and send information from the target to the sink. The gray node is the designated projector node. 3DUT is a two phase algorithm. During the first phase, 'passive listening', sensor nodes listen to the underwater environment for potential targets. The second phase of the algorithm, 'active ranging', is to localize the target. 3DUT selects a projector node which sends pings periodically.

The target is assumed to be a point target so that the echoes are radiated isotropically. Once the echo is received by the projector, it calculates its distance to the target and transmits to the sink node. Sink node uses trilateration to localize the target. The location and the calculated velocity of the target are then exploited to achieve tracking. Depending on the results of the calculations, sink node selects a new projector node.

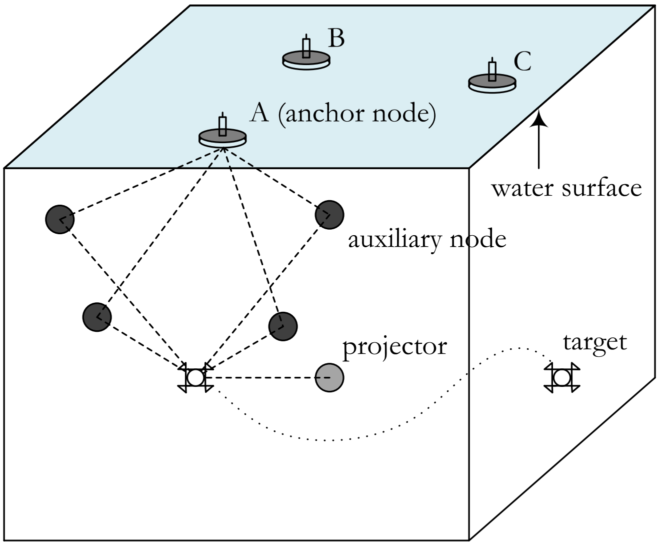

Fig. 2.16 An example of three dimensional underwater target tracking (3DUT)

To save energy, the nodes which are not located at the network edge have low duty cycles. The nodes which are at the boundary of the sensing region have higher duty cycles in order to detect the target entering into the sensing region immediately. Therefore, to avoid rapid energy depletion of boundary nodes due to continuous surveillance, 3DUT employs an adaptive procedure to find, designate, and activate new boundary nodes. Furthermore, it does not depend on the number of nodes. The algorithm runs even if the number of sensor nodes changes. However, it can only track one target at a time. Moreover, the tracking accuracy is heavily influenced by the target's velocity.

2.6.3.2 Distributed Localization

Multi-frequency Active Localization Method based on TDoA (MFALM) is proposed in [129]. In mobile UWSNs, sensor nodes' locations are changed at any time. Location information at a time cannot serve as a reference at the next time. Moreover, in general, only the location information of sensor nodes which detect events is useful for UWSNs. Therefore, it is not necessary to localize all sensor nodes in network, whereas sensor nodes which detect events only need to be localized. There are three types of nodes: buoy nodes, relay nodes and ordinary nodes. After the network is deployed, buoy nodes firstly localize themselves using GPS, and periodically broadcast localization information with low-frequency acoustic signals. Relay nodes communicate with each other with low-frequency acoustic signals to divide the network into multiple localization domains and calculate the value of max hops for each domain. Ordinary nodes which detect event open low-frequency signal receiving devices to receive localization information from buoy nodes and localize themselves. At the same time, the ordinary nodes open high-frequency signal sending devices to broadcast message report package (MRP). MRP contains the detected events and the locations of the ordinary nodes. All ordinary nodes which receive the MRP need to relay the packages and decrease the value of max hops by 1. The package broadcasting stops when the value of max hops is 0 or the MRP is received by any relay node. Relay nodes send the received MRP to buoy nodes for further disposal. After disposing the MRP, buoy nodes will respond with ACK to ordinary nodes. Then, the ordinary nodes go to sleep until new event is detected.

Dive and Rise (DNR), an interesting idea of dive and rise positioning is presented in [130]. DNR anchor nodes are used to replace static ones. Each DNR anchor node is equipped with GPS. While sinking and rising, they broadcast their positions. Unknown nodes are localized by passively listening to DNR anchor nodes' messages. Range measurement is done by using one-way ToA. After hearing from several anchor nodes, unknown nodes estimate their coordinates.

DNR scheme reduces communication overhead and energy consumption by the passively listening method. Unknown nodes spend energy only in receiving and processing localization message. Furthermore, DNR scheme can localize unknown nodes in deep water. However, DNR anchor nodes diving and rising takes longer time than message propagation. Therefore, localization performance heavily depends on frequency of location updates and number of anchor nodes. Compared with LSHL, DNR has higher localization accuracy and less energy consumption and communication overhead [131].

To improve performance of DNR, multi-stage DNR (MS-DNR) is proposed in [132] to speed up the localization process at cost of less accuracy and more messaging. Once unknown nodes become localized, they start to act as reference nodes. Therefore, unknown nodes lying out of the communication range of DNR anchor nodes can be localized by the localized unknown nodes. Similar iterative schemes such as LSHL have been proposed. Communication overhead and energy consumption of MS-DNR are relatively high due to the iterative scheme. For this reason, MS-DNR is less energy-efficient than DNR. Compared with DNR, MS-DNR uses a more realistic underwater mobility model, named meandering current mobility (MCM) model, which has been studied in [133]. The model considers sensor nodes' movement by the effect of meandering sub-surface currents and vortexes. Unlike previous works where nodes are deployed in a small bounded geographic domain, the domain model in MS-DNR is representative of a large coastal environment spanning several kilometers. In this case, assuming sensor nodes uniformly distributed over the large domain is unrealistic. Therefore, it considers an initial deployment of sensor nodes in a small subarea where they are released and thereafter move according to the mobility model. A kinematic approach [134-136] is employed to represent the mobility of underwater sensor nodes drifting with subsurface currents. To the best of our knowledge, this is the first physically-inspired mobility model used in the analysis of mobile UWSNs.

The major drawback of the DNR and MS-DNR scheme is the high expense of DNR anchor nodes. For 25 DNR anchor nodes in 1×1×1km underwater area, 25 GPS and 25 moving equipment are needed, which is very expensive. Moreover, under actual underwater environments, the DNR anchor nodes are strongly affected by the surface currents, which will degrade localization accuracy. Therefore, multi-stage AUV-aided localization (MS-AUV) scheme is proposed in [137] aimed at improving MS-DNR scheme by replacing the DNR anchor node with an AUV.

Scalable Localization scheme with Mobility Prediction (SLMP) is devised in [18] by utilizing the predictable mobility patterns of underwater objects. Localization in SLMP is performed in a hierarchical way. The whole localization process is divided into two parts: anchor node localization and unknown node localization. During the localization process, every node predicts its future mobility pattern according to its past known location information. Moreover, every node can estimate its future location based on its predicted mobility pattern.

It is assumed that every sensor node needs to get its location periodically. During each localization period T_p, anchor nodes can easily measure their locations since they can directly communicate with surface buoys. Based on the measured location loc_m in the last localization period and the predicted mobility pattern, each anchor node can calculate its estimated location loc_e in current localization period. The anchor node compares the estimated location loc_e with its measured location loc_m. If the Euclidean distance between them is larger than the stipulated threshold, the anchor node will judge that its current mobility pattern is not accurate and needs to be updated. Then, it runs its mobility prediction algorithm to get a new mobility pattern. After that, it will broadcast a new localization message which contains its current location and new mobility pattern to the network.

During unknown node localization process, all anchor nodes label themselves as reference nodes and set their confidence values to 1. When an unknown node receives localization information from anchor nodes, it runs its mobility prediction algorithm to estimate its own location and mobility pattern. If any unknown node has not received any localization message for a long period (larger than some predefined threshold), it will label itself as un-localized. With the advance of the localization process, more and more unknown nodes are localized and become reference nodes, as describe in [80, 81]. Simulation results show that communication overhead and energy consumption of SLMP are relatively low. However, the performance of SLMP is easily influenced by the localization period T_p. When T_p is short, a relatively high communication overhead is needed. Furthermore, the performance of SLMP heavily depends on the structure of the mobility pattern.

AUV-Aided localization technique came out in [138], where an UWSN consists of many sensor nodes and one AUV. The sensor nodes are dropped into ocean and move with water currents. The AUV traverses the UWSN periodically following a predefined trajectory (a lattice-like and an Archimedean spiral trajectory). Moreover, all nodes can communicate (omni-directionally) with the AUV. The AUV can surface to obtain its coordinates by GPS, then dives to a predefined depth (provided by pressure sensors) and starts exchanging three types of messages with unknown nodes: wakeup, request and response. 'Wakeup' messages are sent by the AUV as it enters the network to declare its presence to unknown nodes in its communication range. Unknown nodes that receive 'wakeup' respond with a 'request' message to commence range measurement. The 'request/response' messages are exchanged between the AUV and unknown nodes to estimate their positions according to the round trip time. Then, localization is investigated using two methods, bounding-box [102] and triangulation.

Bounding box method draws a rectangular region with the intersection of the distance estimates as depicted in Fig. 2.17. The positions of unknown nodes are obtained by applying the distance measurements as constraints on the X and Y coordinates of unknown nodes. In Fig. 2.17, A and B represent the positions of the AUV at two different time slots and C is the position of the unknown node. If the distance between the unknown node and the position of AUV A is d_{AC}, then the x coordinate of node C is bounded by d_{AC} to the left and to the right of the X coordinate of A, $x_A - d_{AC}$ and $x_A + d_{AC}$. The Y coordinate of node C is bounded by $y_A - d_{AC}$ and $y_A + d_{AC}$. Similarly, the bounds for C's coordinates with respect to B are obtained. The intersection of the diagonals gives the coordinates of the unknown node. The performance of bounding box is highly dependent on the positions of the AUV. An unknown node is better localized if the beacons are sent from opposite sides of the box. Compared with triangulation, bounding-box achieves a higher localization ratio with a higher degree of error.

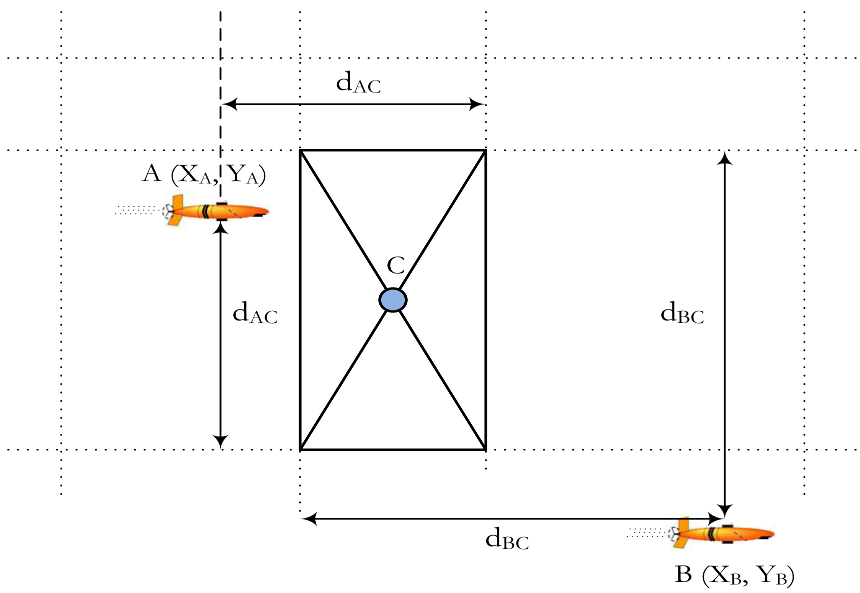

Fig. 2.17 An example of three dimensional underwater target tracking

AUV scheme does not assume any fixed infrastructure or time synchronization. Simulation results show that 100% localization can be achieved with only 3% localization error. However, localization time and accuracy are greatly influenced by the velocity and the location accuracy of the AUV. Since the velocity of the AUV is relatively slow, AUV-aided localization technique has high localization delay which is about up to 2 hours.

To shorten localization time and improve localization accuracy of AUV-aided localization technique, MS-AUV is proposed in [137]. MS-AUV combines the flexibility of the AUV-aided localization and the energy efficiency of 'Silent Localization', which has been studied in [96], where unknown nodes passively listen localization message. Simulation results show that the whole localization process can be completed in less than 10 minutes and can cover more than 95% of the whole network. However, similar to other multi-stage algorithms, e.g., MS-DNR, accumulated error is inevitable.

2.6.4 Finger-printing Based and other Schemes

A different variant of range-free localization schemes based on finger-printing pattern matching (PM), principal component analyses (PCA), and probabilistic fingerprinting (PF) have recently been proposed in [139-141]. Such schemes involve an offline (or training) stage prior to the online (or prediction) stage. The setup comprises an acoustic signals source capable of transmitting at M different frequencies, and L reference locations with known positions and a node (receiver) to be localized.

During the offline stage, the receiver is placed at each reference location (with known position), collects N samples of acoustic communication signals at each frequency to constitute an $M \times N$ acoustic signals map. All the signals are projected onto the eigenspace for principal component analysis, where M' signals corresponding to the largest eigenvalues are extracted in order to reduce the complexity and noise effects. This is repeated at the L reference locations. In the online stage, the receiver is placed at an unknown location (within the reference location space) and collects acoustic communication signals from M different frequencies to establish a signal vector, from which M_0 principal components are extracted as in the offline stage. A likelihood function is used to express the probability that the unknown location corresponds to a reference one, and the unknown location can then be estimated by the 'probabilistic weighted' summation of different reference locations. The efficacy of the proposed scheme has been verified in actual experiments in a water tank. However, the practical use of this scheme is limited since the actual underwater acoustic channel in the sea is highly time varying [142].

Silent Localization Using Magnetometers (SLUM) is a scheme where it uses magnetometers as means of localization. As mentioned earlier, unknown nodes localization in UWSNs is traditionally addressed using acoustic range measurements involving known anchors or surface nodes. However, sound scatters significantly in underwater environments, especially in shallow water [143] where magnetometers could be more useful than acoustics. Magnetometers and the magnetic dipole of a vessel for target tracking have been explored in [144, 145]. In [146], silent localization using magnetometers is proposed. And this may be the first time magnetic dipole tracking is used to localize unknown nodes. SLUM silently localizes underwater unknown nodes equipped with triaxial magnetometers using a friendly vessel with known magnetic dipole. Unknown nodes are localized by listening to the messages of the dipole. The ferromagnetic field created by the dipole is measured by the magnetometers and is used to localize unknown nodes. Each unknown node is further equipped with a pressure sensor and an accelerometer used for depth estimation and sensor orientation estimation, respectively. The trajectory of the vessel and the positions of unknown nodes are estimated simultaneously using an extended Kalman filter (EKF) [146, 147]. In SLUM, sensor nodes are assumed to be connected by wire; as a consequence, common problems in UWSN such as time synchronization, limited bandwidth, and limited energy resources are neglected. However, the additional hardware requirement is the drawback of SLUM which makes it costly and non-pragmatic.

Probabilistic Localization Method (PLM) is to mitigate distance measurement error in localization process, multi-iteration measurement and least squares scheme are often adopted in terrestrial applications as depicted in [148]. However, in underwater applications, the multi-iteration scheme is not practical due to high communication cost. Meanwhile, it has been observed that the probability distribution of distance measurement error often follows a certain pattern, which can be utilized to further improve localization accuracy. In this scheme both uniform error distribution and normal error distribution are considered to improve localization accuracy.

PLM method consists of two steps. In the first step, every two neighboring anchor nodes calculate positions of unknown nodes using a circle-based or hyperbola-based approach. The second step is to determine the final locations of unknown nodes by using the probability distribution of distance measurement error. Localization coverage and accuracy can be improved by utilizing more anchor nodes. However, computation complexity and energy consumption increase greatly. Simulation results indicate that PLM method can significantly improve localization accuracy. Compared with other methods, e.g., minimum mean absolute error (MMAE) and minimum mean squared error (MMSE) based statistical approaches, PLM method requires less information exchange. However, the two ideal error distributions may not make sense in real UWSNs environment.

Node Discovery and Localization Protocol (NDLP) is proposed in [149, 150] to manage sub-sea localization. As shown in Fig. 2.18, NDLP starts with one seed node (primary seed S_1) with known position. The primary seed node is capable of determining the relative positions of neighboring nodes. A second seed node, S_2 is then chosen by S_1. S_2 is the most distant node within the communication range of S_1. The advantage of choosing the farthest node as the second seed node is that a larger area can be covered more quickly. A third seed node S_3 is chosen from those nodes that lie in both communication ranges of S_1 and S_2, and has the maximum summation distance from S_1 and S_2. Each node in the overlapping region, the grey area in Fig. 2.18, is able to calculate the relative location using a simple triangulation technique. The nodes in the cross-hatched region in Fig. 2.18 can only obtain two distance measures from seed nodes. In order to localize the nodes in the cross-hatched region, a fourth seed node is selected.

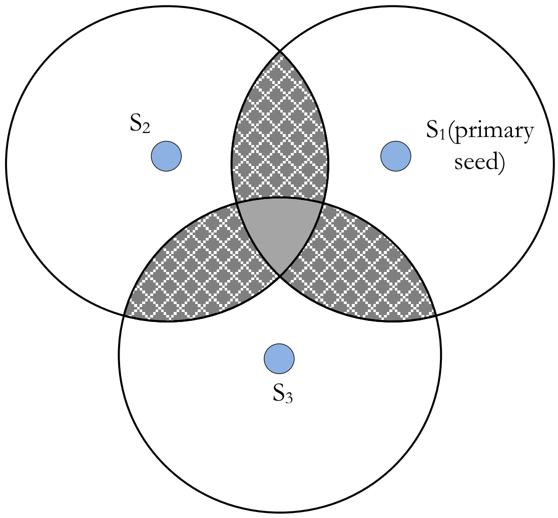

Fig. 2.18 An example of node discovery and localization protocol (NDLP)

NDLP is an anchor-free and GPS-less algorithm. Large scale of unknown nodes can be localized by continuously selecting seed nodes. However, NDLP has some serious problems. First, the node discovery phase needs much communication overhead. Each node participates in massage exchange to select seed nodes. Hence, energy consumption of node discovery is high. Second, the seed node's selection process takes long time, hence localization time is long. Moreover, unknown nodes' relative coordinates calculated based on the seed nodes' positions are not accurate. In some areas, if nodes are much sparsely deployed or become sparser due to some movements, then it is possible that very few or even no node can be selected as seed node. It is shown that NDLP is not suitable for sparse and mobile UWSNs. Furthermore, in mobile UWSNs, repeating the node discovery each time the topology changes is unaffordable.

Underwater Sensor Positioning (USP) scheme is proposed in [151, 152] for sparse 3D UWSNs, as shown in Fig. 2.19. At least three anchor nodes are included in the network. To simplify the process of endowing anchor nodes with their positions, they are placed at the surface as GPS-enabled buoys. In USP scheme, unknown nodes get their depth information by pressure sensors. The depth information is used to transform the 3D underwater positioning problem into its 2D counterpart via the projection technique. For example, consider an unknown node U that needs to compute its position within a 3D oceanic deployment area. It is assumed that node U is within communication range of three anchor nodes A, B and C located at known positions (x_A, y_A, z_A), (x_B, y_B, z_C), and (x_C, y_C, z_C) respectively. Given U's depth information z_U, node A is projected as node A' located at position (x_A, y_A, z_U). Nodes B and C are projected as nodes B' and C' located at position (x_B, y_B, z_U) and (x_C, y_C, z_U). After three anchor nodes A', B' and C' have been projected, elegant localization methods such as simple bilateration can be employed to localize node U.

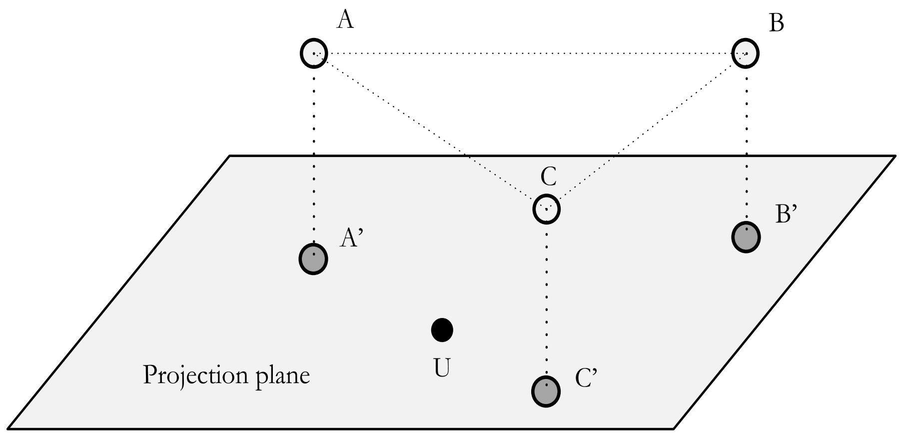

Fig. 2.19 An example of underwater sensor positioning (USP)

USP scheme first uses depth information to localize unknown nodes in sparse 3D UWSNs and has low storage and computation requirements. USP scheme seems simple by introducing pressure sensors. However, installing pressure sensors increases energy consumption per unknown node; hence decreasing the life time of the UWSNs. Moreover, USP scheme has low localization success. In addition, each unknown node consumes much energy to map the available anchor nodes on the horizontal plane it resides on. Furthermore, unknown nodes in deep water cannot be localized because they may be out of the anchor node's communication range.

2.7 Problems and Limitations

Most of the localization algorithms that are suitable for terrestrial environment possesses difficultly and in some cases almost impossible to use in underwater localization due to harsh environment. Moreover, the variable nature of underwater environment and limitations in using signals made it more difficult in localization arena; whereas localization in underwater is as important as terrestrial. Any scheme that relies on ToA or TDoA requires tight time synchronization between the transmitter and the receiver clocks. Moreover, TDoA schemes determine the time difference of received signal between multiple receivers, where to localize one sensor node multiple receiver nodes are necessary. One simple way to achieve synchronization between the receivers as well as between transmitter and receivers in terrestrial networks is to use radio signals. The luxury of using RF signals for time synchronization is not readily available in the underwater scenario as RF waves do not propagate well underwater. But, with the advancement of sensors' capability in measuring received signal strength and choosing the right frequency shows the possibility of using radio signals underwater. However, the propagation distance of radio signals is confined within few hundred meters. If problem domain is out of this scope, it would be practical to use acoustic signals for measurement purposes. The speed of sound is assumed to be constant in many schemes, while the speed of sound is a function of temperature, salinity and depth. It is conspicuous that schemes that take into account the variation in the speed of sound are expected to perform better than those that just assume a uniform speed of 1500m/s. As range-based localizations perform better in underwater environment than range-free - it is important to determine the average acoustic speed to calculate distances. If not, this distance error will propagate further to generate higher degree of positional error.

Multipath fading is one of the major influencing factors while determining distance between transmitters and receivers with the help of RSSI. There are other environmental as well as physical factors that affect the signal strength. Like acoustic signals are affected by reflection and refraction due to sea surface and seabed. Typical frequencies associated with underwater acoustics are between 10Hz and 1MHz. The propagation of sound in the ocean at frequencies lower than 10Hz is usually not possible without penetrating deep into the seabed, whereas frequencies above 1MHz are rarely used because they are absorbed very quickly. So for any appropriate acoustic frequency that is used in underwater to measure the propagation loss is affected by multipath fading. Experiments reported in [153] have shown that multipath effects can be modelled as Rayleigh fading in shallow water environments. Acoustic signals, apart from undergoing large scale spherical or cylindrical losses under water, also undergo attenuation losses and losses due to air bubbles, and are subjected to external sources of noise like ship and shrimp noises.

Several range-based localization schemes for terrestrial sensor networks are based on AoA, where sensor nodes calculate the relative angles between neighboring nodes. However, schemes that use AoA entail sensors and anchor nodes to be equipped with special antenna configurations which may not be feasible to embed on each sensor, let alone underwater sensors where mobility and external force in some case is inevitable. Such schemes also involve solving complex non-linear equations [154].

Range-free schemes offer a less precise estimate of location compared to range-based schemes. Range-free schemes are useful in the context of terrestrial sensor networks, where sensor nodes might not be capable of sending acoustic signals for ranging purposes. In the case of underwater sensor networks, acoustic signals can be used for fairly accurate ranging. However, there are scenarios where a coarse estimate of the node's location might suffice. For example, geographical routing protocols could use the coarse location information obtained from range-free schemes for establishing source-destination paths. On the other hand, finger printing based schemes are suitable for a static environment; not suitable at all for dynamic underwater environment.

To the best of our knowledge, most of the localization algorithms uses multiple reference points which is not as practical as using a single reference point. A few uses single submerged mobile reference point with the limitation of its position is preset or known. To know or preset the location of a mobile reference point possesses another challenge. Having preinstalled infra-structure for localization purposes is cumbersome and not dynamic at all. So the localization of submerged sensors in a pragmatic fashion is what the time demands. Following table summarized different localization schemes.

Methods	Features and limitations
Seaweb and Prospector [78]	Four acoustic transponders are deployed on the seabed at known locations, with surface or sub-surface floats. Moreover, the major limitation of infrastructure-based positioning schemes is that it is not dynamic.
LSHL [80, 81]	Where surface buoys drift on water surface and get their locations from GPS. LSHL has inherent problem of confidence threshold, which can affect its performance.
UPS [95, 96]	It requires no time synchronization and has low computational overhead. It also does not take into account the impact of transmission failures, which is very likely because underwater acoustic channels are unreliable.
LSLS [99]	LSLS localizes more unknown nodes than USP does. However, more energy and communication overhead are consumed to implement its three-phase localization.
3DUL [107]	Non-linear dynamic trilateration method is used which does not guarantee a solution. This overhead of computational complexity of this scheme is huge and not feasible for a dynamic environment.
ALS [112]	The main responsibility of anchor nodes is to send out signals with different levels of power to localize unknown nodes. The advantages of ALS are being range-free and having no synchronization requirement.
LDB [118]	AUV traverses a preprogramed route and performs directional (vertical) beaconing periodically. Its localization coverage is limited; hence, LDB is not suitable for large scale UWSN.
RSMB [119]	Where a mobile anchor node moves on the sea surface at a constant speed and broadcasts signals at a regular intervals. Localization time and accuracy mainly depend on the beacons' sending interval and the path planning of the mobile anchor node, which severely affects localization accuracy.
APS [121]	APS is proposed to localize one AUV only and localization coverage is limited by the acoustic interrogation pulse. Installation of transponder at the sea bed beforehand is necessary which makes is not dynamic at all.
MASL [125]	MASL is a centralized anchor-free localization algorithm, which reduces unknown nodes' computational burden and can be used to localize large scale UWSNs. The problem is that the iterative algorithm cannot provide real-time location information.
CLS [127]	A profiler travels to a depth first then followers travel the trajectory of the profiler. For a sparse or non-homogenous network, the performance of can be affected significantly. In order to get higher localization accuracy, the profilers have to stay closer to the followers.
3DUT [128]	At least three anchor nodes float at the surface of water, it can only track one target at a time. Moreover, the tracking accuracy is heavily influenced by the target's velocity.

DNR [130]	Each DNR anchor node is equipped with GPS. While sinking and rising, they broadcast their positions. Anchor node's diving and rising takes longer time than message propagation. Therefore, localization performance heavily depends on frequency of location updates and number of anchor nodes.
SLMP [18]	SLMP localizes by utilizing the predictable mobility patterns of underwater objects. Communication overhead and energy consumption of this method are relatively low. However, the performance of SLMP is easily influenced by the localization period.
AUV-Aided [138]	This scheme does not assume any fixed infrastructure or time synchronization. However, localization time and accuracy are greatly influenced by the velocity and the location accuracy of the AUV itself.
SLUM [146]	It uses magnetometers as means of localization, where sensor nodes are assumed to be connected by wire; as a consequence, common problems in UWSN such as time synchronization, limited bandwidth, and limited energy resources are neglected. However, the additional hardware requirement is the drawback of SLUM which makes it costly and non-pragmatic.
NDLP [149, 150]	Large scale of unknown nodes can be localized by continuously selecting seed nodes. If nodes are much sparsely deployed or become sparser due to some movements, then it is possible that very few or even no node can be selected as seed node. Furthermore, in mobile UWSNs, repeating the node discovery each time the topology changes is unaffordable.
USP [151, 152]	At least three anchor nodes are included in the network. This scheme has low localization success. In addition, each unknown node consumes much energy to map the available anchor nodes on the horizontal plane it resides on.

Chapter 3

METHODOLOGY

The background and literature review in the previous chapter reveal that much research has been carried out on localization without careful consideration to the speed variation of acoustic signals in underwater; moreover multiple beacons are deployed ahead of time, and in some cases beacons' position is predefined. Furthermore, some schemes delineate mooring beacons on to the sea bed as well as driving AUV in a predefined course, which is not dynamic and requires predefined infrastructure; besides determining and keeping AUV in course is quite cumbersome. This chapter describes the overall methodology used in this research. It contains a description and evaluation of the methods, techniques and procedures used in the investigation and analysis. The scope and aims of the report are also covered in detail.

From the problems and limitations discussed in the previous chapter, there are some important research questions to be addressed in the field of underwater wireless sensor networks. The research questions we identified for our research are reported in the following section.

3.1 Research Question

How to determine the coordinates and bearing of the submerged sensors accurately using a single beacon?

Sub-research Questions

1. How to determine the distance between the beacon and the sensors keeping multipath impact as low as possible?
2. How to determine the acoustic speed in a vertical water column efficiently, using the data gathered from the submerged sensors?
3. How to estimate the effect of parallel plane on coordinate determination?

3.2 Hypothesis

The research questions are addressed by the following hypothesis.

1. Recent studies show that it is possible to use radio signals in underwater environment; by carefully choosing the right frequency for both radio and acoustic signals, we propose an algorithm to determine the flight time of the acoustic signals that eventually avoids and minimize the multipath impact of the signals.
2. We propose a mathematical model to consider acoustic speed at each points of the vertical water column and to calculate the average speed of the acoustic signals.
3. Linearized Cayley-Menger determinant can be used to determine the coordinates of the sensors while the sensors are stationary.
4. Parallel plane effect constraint in Cayley-Menger determinant can be solved by shifting the unparalleled plane to an imaginary point where the plane is parallel with water surface.

3.3 Research Methodology

A schematic representation of the methodology is shown in Figure 3.1. There are three major phases and the activities in each phase are given below:

- Investigation and Analysis
  - Examination of UWSN Environments
  - Examination of different problem domain in underwater
  - Examination of the methods used for localization
- Identify Problems and Solutions
  - Identify affecting factors

- Propose algorithms
- Eliminate factors

- Design System Component and Test
  - Develop mathematical model
  - Performance analysis
  - Recommend solution
- Integrate System Component and Evaluation
  - Evaluate system in simulated environment
  - Performance in different scenarios
  - Recommendation

Fig. 3.1 shows the order in which the activities in each phase will be executed. There are four starting activities in the Investigation and analysis phase. After the Examination of UWSN Environments and Different Underwater Problem Domains, different localization processes are analyzed. Thereafter, the factors that influence the distance measurements were identified. Once this has been achieved, the next stage is to propose algorithms to eliminate those affecting factors. When the Identify Problems and Solutions phase is completed, the next phase is Design System Component and Test, where a mathematical model will be developed. The developed mathematical model will be tested in a simulation environment and performance will be analyzed. If a suitable algorithm and solution is found supported by appropriate performance results, a solution to that problem will be proposed. However, if no algorithms and solutions are found to be suitable, then new algorithms will need to be developed in the Propose Algorithm stage.

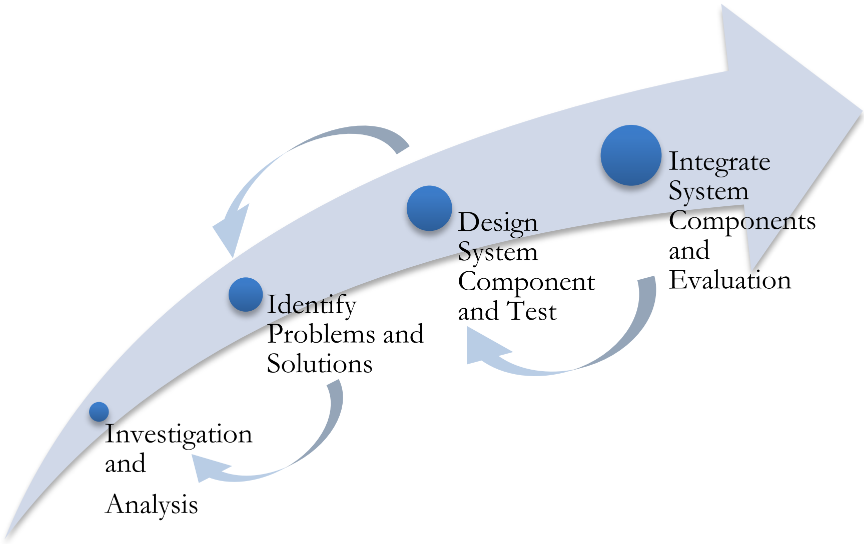

Fig. 3.1 Methodology with agile capability

After the Design System Component and Testing phase, the entire developed component will be integrated and evaluated for different scenarios. Comparing the performance recommendation will be made.

3.3.1 Investigation and Analysis

Investigation and Analysis phase has three steps, as shown in Fig. 3.2. Underwater networks and the environment are very diverse and dynamic. Its characteristics depend on various factors like, temperature and salinity of water, turbidity, depth as well as geographical location on earth. Encompassed in the scope of our research, UWSN environmental factors, different problem domain and methods of localizations are explored in the following sections.

3.3.1.1 Examination of UWSN Environments

Examining and analyzing UWSN includes- sensors used for data communication and data collection as well as the environmental factors affecting the estimation of the location of sensors. The underwater sensors come in different shapes and types. Some are stationary while some are mobile; some are controlled and some follow predefined routes. Type of signals used for communication purposes and for localization is influenced by several factors, such as temperature, depth and salinity; these variables are dynamic in underwater environment. Besides, the number of sensors can be from few to thousands in different depths of the water column. These mobile submerged sensors are battery operated, so the energy consumption should also be considered while proposing solutions.

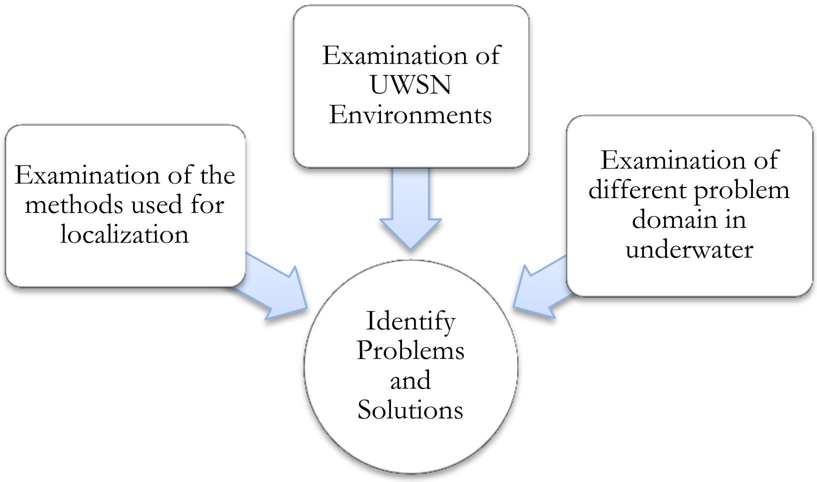

Fig. 3.2 Investigation and analysis as part of the methodology

3.3.1.2 Examination of different problem domains in underwater

In this step of Investigation and Analysis phase; different problem domains are explored and examined. Localization is needed in shallow to deep water columns where the range could be from hundreds to thousands of meters. The sensors can be in any depth of the water column. Depending on the position of the sensors and the depth of the water column various localization techniques exist. As most of the underwater exploration takes place in shallow water, our methodology is focused on to propose shallow water localization scheme in pragmatic fashion. We propose the number of beacon nodes that will float on the surface of the water is one and minimum of three underwater deployed sensor nodes, which is achievable number of sensors in UWSN.

3.3.1.3 Examination of the methods used for localization

In this step we study the various localization techniques used based on the problem domain; as there can be various problem domains and associated localization solutions. Each solutions and problem domains have been explored and carefully examined for merits and demerits. Associated localization error varies from centimeter to tens of meters depending on the scenarios. Some proposals use predefined infrastructure with known coordinates of the beacon or reference nodes.

3.3.2 Identify Problems and Solutions

In this phase of Identify Problems and Solutions; problems and factors that feed errors into localization have been identified and a solution to mitigate the problem has been proposed. This phase has three steps like in the previous phase as can be seen in Fig. 3.3. Amongst factors, propagation range of different signals and speed is one of the major factors while the algorithm itself plays a significant role. In the following sections these issues are discussed.

3.3.2.1 Identify affecting factors

In this step, factors that are influencing negatively in the determination of the submerged sensor nodes are identified. Among these factors, speed of acoustic signals used for distance determination, algorithms in play and the method of coordinate determination are prominent.

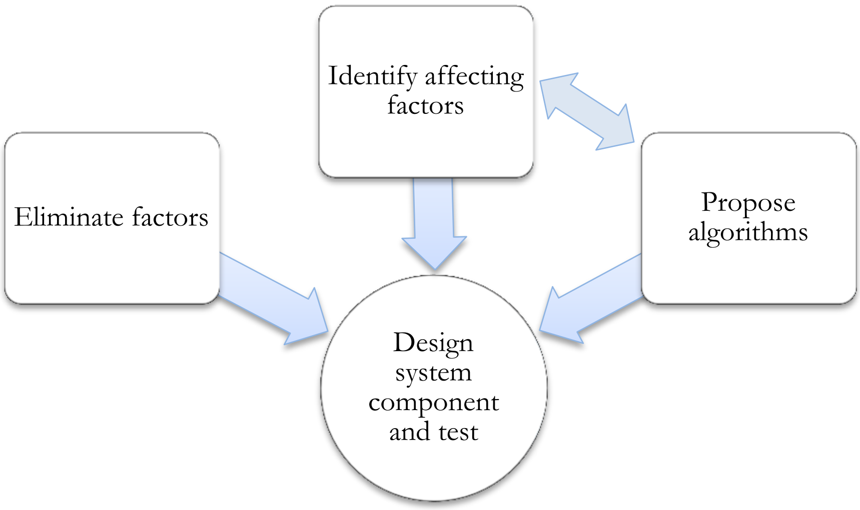

Fig. 3.3 Identify problems and solution as part of methodology

Sub-research question 1 and 2 can be partially addressed here. To determine the distance between the beacon and the sensors using acoustic signals, various techniques can be found. For example, the RSSI of signal at the sensors could be measured and from the relation between signals propagation and the strength of the signal, distance can be measured. In this technique, multipath phenomenon of signal propagation exists and can give erroneous result in distance determination. Other technique, like bouncing technique where an acoustic packet is transmitted towards the sensors from the beacon and the sensor nodes resends the same packet towards the beacon after receiving it. The total travelled time is recorded and from the relation between time travelled by the signal and speed of the signal - the distance is calculated. A proper communication channel and protocol needs to be established for this technique of localization; the speed of the acoustic signals needs to be determined precisely beforehand for the water column. Moreover, time requires to receive the packet and to process information as to determine the sender will incorporate multipath fading effects, which eventually will give a distance greater than the true Euclidean distance.

Determination of speed of acoustic signals in underwater is a vital factor for accurate determination of distance between beacon and sensors. Usually the speed is assumed to be 1500m/s regardless of the condition of the problem domain. Few equations are capable of determining the speed of acoustic signals for a single point once the temperature, depth and salinity of that point is known. In this part of the methodology, to determine the distance between beacon and sensors precisely, average speed of acoustic signals for a vertical water column is identified to be a potential factor. All the identified characteristics that are important in determining the exact coordinates include:

- Multipath fading impact
- Average velocity of acoustic signals for vertical water column should not be assumed 1500m/s; it should be calculated
- Solving system of nonlinear equations so that the errors remain minimum
- Solving voluntary or involuntary mobility of the sensors

3.3.2.2 Propose algorithms

Once the influencing factors are identified, this step of Identify Problems and Solutions phase focuses on the addressing algorithms to mitigate the factors identified in the earlier step. Proposed algorithms will be tested in simulation environment to validate its feasibility and preciseness.

Sub-research question 1 and 2 are addressed in this step. To determine the distance between the beacon and the sensors both radio and acoustic signals will be used. Time difference of arrival of the radio and acoustic signals will be used to determine the flight time of the acoustic signals from beacon to the deployed underwater sensor nodes. The beacon will have the ability to generate radio and acoustic signals at the same time and the sensor nodes will be able to detect the presence of radio and acoustic signals. Time difference will be recorded and transmitted to the beacon using acoustic signals with single message. The recorded flight time will be used to calculate distance between beacon and sensor nodes after determining the average speed of the acoustic signals for the water column in the problem domain.

By solving the conventional multivariate equation for underwater acoustic speed at each points and eliminating variables, we propose to calculate the average speed of the acoustic signals in the vertical water column. As speed of acoustic signals varies at each point of the water column, average speed of acoustic signals for the problem domain is vital to determine the coordinates of the sensors correctly. Moreover, the developed mathematical model proves the accuracy of the sensors' coordinates depends on preciseness of the distances measurements.

3.3.2.3 Eliminate factors

In this step, aforesaid factors will be eliminated by applying proposed algorithms. The impact of multipath effect can be minimized if flight time of the signals is measured instead of measuring the signal strength. Signal strength of any signal is the combination of the various reflected signal components from the beacon to the sensors where multipath fading is very prominent. Whereas if the presence of the signals is measured, the signal component that travels the Euclidean distance will reach to the sensor nodes at the earliest. In this way, impact of multipath fading can be minimized.

Calculating the average speed of the acoustic signals for the vertical water column eliminates assumed value factor used in localization. The multivariate equation of acoustic signals for a point is solved for the gathered data by the beacon as well as the sensors and elimination of variables gives the average speed of acoustic signals. The speed of radio signals in underwater is predetermined by the research community and does not change because of change of environmental variables, as with the case of acoustic signals. Other factors are eliminated in the following phase.

3.3.3 Design System Component and Test

In this phase aforesaid solutions for identified problems will be designed and tested. The steps of this phase are shown in Fig. 3.4.

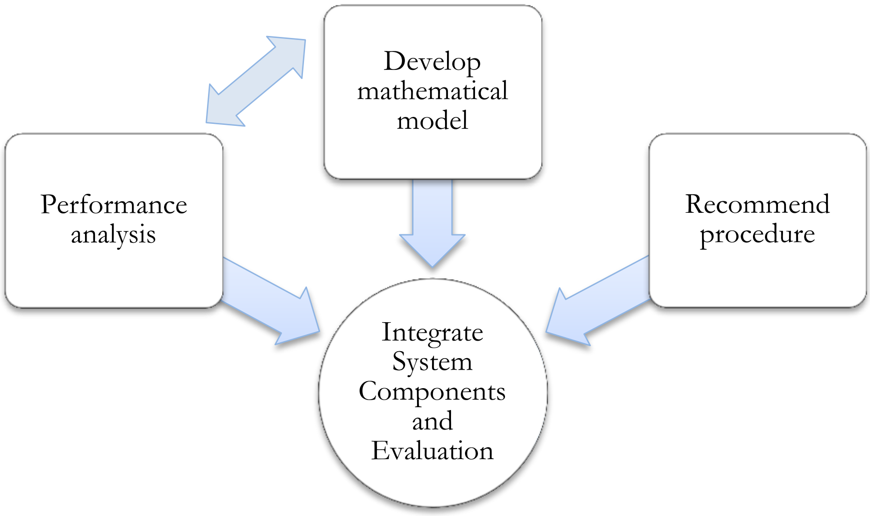

Fig. 3.4 Design system component and test as part of methodology

3.3.3.1 Develop mathematical model

In this step, a mathematical model is developed for the proposed solution. To determine the coordinates of the sensors with respect to one of the sensors, Cayley-Menger determinant is used. Cayley-Menger determinant gives the volume of a tetrahedron created by one beacon at the surface and three sensors at the bottom of the water column; it is worth noting that the volume of the tetrahedron is given with respect to the distances between beacon and sensors as well as inter sensors distances. As the determinant is nonlinear, to use the merit of degree-of-freedom the expanded determinant is linearized and solved. Once the coordinates of the sensor are found with respect to known distances, trilateration and linear transformation of the reference point are used to determine the coordinates of the sensors with respect to the beacon node.

At first the coordinates of the submerged sensors are determined assuming the sensors are stationary; voluntary or involuntary mobility of the sensors will be incorporated into the mathematical model later on.

3.3.3.2 Performance analysis

Performance will be measured in simulated environment using Matlab. After testing the individual solutions the mathematical model is tested to find the degree of accuracy of the model considering distances as true Euclidean distance. Afterwards, Gaussian noise is applied to the distances and coordinates are found. The coordinates with and without Gaussian noise is compared to calculate positional errors of the sensors.

The simulation tool Matlab is also used to determine the average speed for the vertical water column as well as the effect of temperature, depth and salinity on average speed of acoustic signals. These different levels and types of effect by temperature, depth and salinity are compared for any individual water column to decide which factor/s needs more consideration and attention at the time of localization. The performance of the mathematical models and algorithms are tested in simulated environment keeping the environment as pragmatic as possible.

3.3.3.3 Recommend procedure

In this step of the Design System Component and Test phase, analyzing the result from the previous step, each component's procedure will be recommended to determine coordinates as well as for other necessary specifications and values. To illustrate, what kind of acoustic signals will be used so that sensors can detect it while being in the surrounding noise; and to cover the required distance with radio signals in underwater, correct range of frequency will be recommended.

Besides, we will propose the trajectory of beacon's movement while measuring distances between beacon and sensors; it should be such that the matrix formatted in mathematical model avoids singularity. To be in a reasonable range of positional error, this step will recommend the ranges of the sensors could be apart from each other.

3.3.4 Integrate System Components and Evaluation

In this phase of research methodology all of the developed components will be integrated and tested for performance. The steps of this phase are elaborated in following sections.

3.3.4.1 Evaluate system in simulated environment

Once individual component that were developed earlier performs and produce results within expected range, in this stage, all of them will be put together and tested in a simulated environment. The performance of those individual components will be evaluated to see how they behave and produce results in an integrated form with other components. The collective results of the integrated system will address research question as well as sub-research questions 3 and 4.

Sub-research question 3 will be addressed taking the result produced in sub-research questions 1 and 2 as input. In other words, after the main two stages- 'determining the average velocity of acoustic signals for a vertical water column' and 'determining the distances between the beacon and sensors', coordinates of the submerged sensors with single beacon will be performed. If the simulated result validates the proposed mathematical model of coordinate determination, the model would be tested for various scenarios that resemble the reality in the following sections.

3.3.4.2 Performance in different scenarios

In this step of Integrate System Components and Evaluation phase, errors will be incorporated to resemble real world scenarios to test the integrated model. First of all, all the variables like temperature, depth and salinity of water that affect the velocity of acoustic signals will be injected with errors to see the range of positional errors of the submerged sensors. We can conclude from the performed preliminary experiment that, for the proposed problem domain- temperature would have the greater effect than that of depth and salinity variations. Errors in temperature measurement both at the surface and bottom would differ a great deal because of its accessibility; error in temperature reading at the bottom by sensor nodes would be greater than that of temperature reading at the surface by the beacon. Likewise salinity at the surface of the water column would be much precise than salinity at the bottom surface which could be measured by the sensors incorporated with the submerged nodes. Errors in depth measurement would propagate from errors in pressure measurement at the bottom by the pressure sensors because the measured pressure will be converted to depth using equation in [155]. Considering other factors, errors would be incorporated to depth measurement to see the effect on average speed of acoustic signals for the vertical water column of the problem domain.

After introducing errors in the variables that influence acoustic velocity, errors will be incorporated in flight time of acoustic signals, as distance between beacon and sensors are determined by the product of flight time of acoustic signals from beacon to sensor and average acoustic speed in the water column. So, errors in timing and errors in variables would produce a distance with errors which will be used to determine coordinates of the sensors; this determined position will be compared with coordinates found using the mathematical model without incorporated errors. In future, other scenarios will be tested with sensors' mobility (voluntary or involuntary) on coordinates determination.

3.3.4.3 Recommendation

In this step of Integrate System Component and Evaluation phase, recommendations will be made regarding the overall model for coordinates determination of the submerged sensors with as low as single beacon. In recommendations, depending on the propagation distance of radio signals, the limitations of the depth of problem domain will be made. Besides, the orientation of the beacon while measuring distance to avoid the singularity state of the matrix as well as the limitation in the position of the sensors apart from each other will be stated.

The frequency range of radio signals and specifications of the acoustic signals will be elaborated and recommended depending on the literature reviews and implementation perspective.

3.4 Summary

Methodology is a systematic way to solve a problem. In this chapter, the research question has been identified with some proposed hypothesis. How these hypothesis are tested and the research question is addressed is explained in the previous sections. The total research methodology is divided into four phases and each phase constitutes a number of activities. In the following chapters, the aforesaid steps are followed to design and develop a solution for the above mentioned research questions.

Chapter 4

DISTANCE DETERMINATION

Distance determination is the determining factor in our proposed coordinates determination method with a single mobile beacon. As the proposed mathematical model of coordinates determination in Chapter 5 proves to be accurate with Euclidean distances; in this chapter we delineates method to calculate *in-situ* average acoustic speed from the environmental variables around sensors and beacon. This process is compatible for a dynamic problem domain.

4.1 Introduction

To localize underwater sensor nodes with a single mobile beacon in dynamic fashion, two aspects play important role; i.e., how precisely the inter distances are measured and how mathematically accurate the coordinates determination process is. As range-based methods are more precise than range-free method, we intend to explore range-based techniques. Signals propagation and type of medium used in underwater to measure distances is another factor that contributes to accurate localization. Acoustic signals have been the proven technology for the last few decades in underwater communications and distance measurements in a versatile way; on the other hand light waves performs well in clear and short distance problem domain. With the advent of incorporating fourth generation computing into the sensors as well as the efficiency the sensors achieved, it is now indispensable to reconsider the use of radio signals in limited fashion to enhance the ability to measure distances precisely. Radio signals travel much faster with limited propagation distance whereas acoustic signals travels slower with longer propagation distance, as elaborated in section 2.3.

Despite the underwater limitations of both radio and acoustic signals, we propose to use each of its merit in our method to minimize the error in distance measurement. In our method, radio signals will be used to measure the flight time of the acoustic signals to calculate *in-situ* average speed as acoustic speed varies significantly depending on ambient factors. So this very factor necessitates *in-situ* acoustic speed determination instead of considering 1500m/s by default. Just because distances between the beacon and deployed underwater sensors are the determining factor for our proposed accurate localization as a whole, we tend to achieve such using both radio and acoustic signals. Moreover, acoustic signals will be used for communication purposes also. Even though the speed of radio signals is little less than that of in the vacuum, considering the problem domain, the reduced speed will not affect the proposed localization method significantly. Furthermore, the speed of acoustic signals which varies due to temperature, depth and salinity of the problem domain are the only variables that we need to consider for distance determination between beacon and deployed sensors.

4.2 Problem Domain

In the case of underwater localization, the usual and a pragmatic configuration could be a boat at the surface and sensors deployed underwater as depicted in Fig. 4.1. As the boat is usually mobile in nature and our proposed method also requires a mobile reference point making the method pragmatic and usual.

Besides, static reference point is cumbersome and time consuming to achieve for dynamic localization. As most of the marine exploration takes place in shallow water (100 – 200m in depth), it would be within the range to use radio signal for synchronization. In the proposed method we need at least three sensors and a floating beacon where only information will be used is the distance measurement between them. In the marine environment the deployed sensors can be in any level of the water; some sensors are deployed to float submerged freely or on the bottom surface to collect data. On the other hand, AUV or UUV are sometimes deployed and cruise maintaining a certain height. In any configuration as long as the depth of the problem domain remains within radio signals range (1.8 – 323m) [20], the proposed distance determination technique could be used.

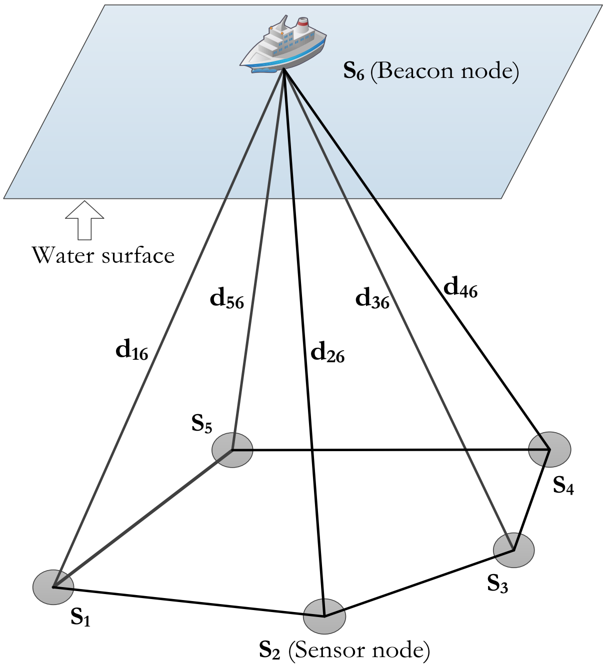

Fig. 4.1 Usual subset composed of one beacon and submerged sensors

In case of higher problem domain depth, clock synchronization could be avoided using radio signals, may be two-way message transfer could be used instead. We are mainly focused on the problem domain which is shallow in depth so that we can use radio signals for synchronization. Beacon node (boat) at the surface of the water will be generating signals to measure the distances following procedures mentioned in the following sections.

Our proposed method requires one beacon at the surface and at least three deployed sensors; a solvable configuration of one beacon with three submerged sensors is denoted in Fig. 4.2. As UWSN consists of sensors ranging from a few to even thousands, three deployed sensors or nodes to collect data that need to be localized is a practical and common number. In case higher numbers of sensors need to be localized, three at a time should be followed. For the sake of simplicity, at present we assume that the submerged sensors are static for the time of computation – the time that is required to measure the distances from different positions of the beacon. As we are using the merits of both signals in the water that restricts the limit of our problem domain to be shallow in depth; which eventually serves our purpose, because most of the marine explorations takes place on the shallow water. The deployed sensors will be equipped with temperature sensor which is very cost effective compared to other parameters sensing capability.

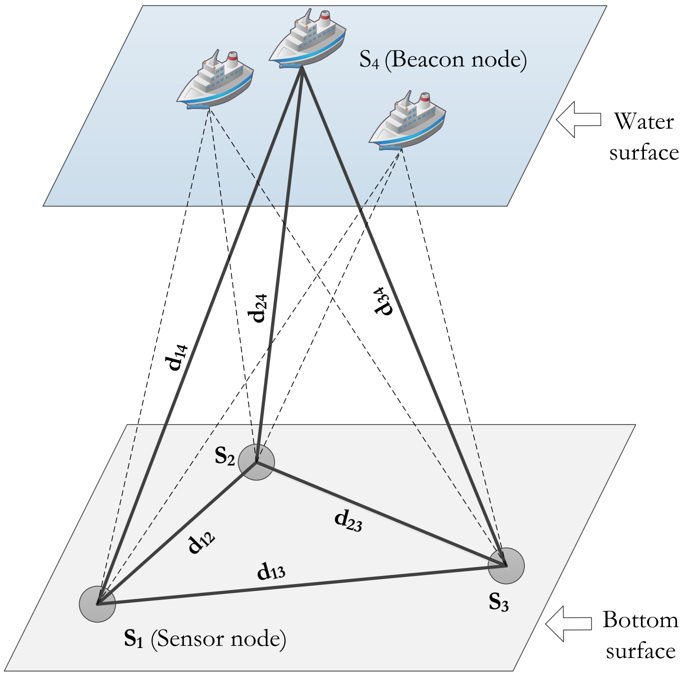

Fig. 4.2 Solvable subset configuration with a mobile beacon and three submerged sensors

4.3 The Effect and Avoidance of Multipath Fading

Multipath formation in the ocean is governed by two effects: sound reflection at the surface, bottom and any objects, and sound refraction in the water. The latter is a consequence of sound speed variation with depth, which is mostly evident in deep water channels.

Typical frequencies associated with underwater acoustics are between 10Hz and 1MHz. The propagation of sound in the ocean at frequencies lower than 10Hz is usually not possible without penetrating deep into the seabed, whereas frequencies above 1MHz are rarely used because they are absorbed very quickly. So for any appropriate acoustic frequency that is used in underwater to measure the propagation loss is affected by multipath fading. Fig. 4.3 and 4.4 shows the obvious present of multipath fading; the impulse response of an acoustic channel is influenced by the geometry of the channel and its reflection properties, which determine the number of significant propagation paths, their relative strengths and delays. Strictly speaking, as there are infinitely many signal echoes, the resultant signal at any point would be $\sum_{i=0}^{\infty} f_i$; but those that have undergone multiple reflections and lost much of the energy can be discarded, leaving only a finite number of significant paths.

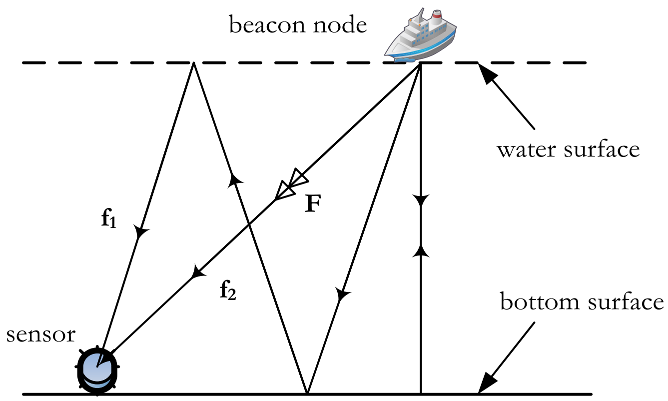

Fig. 4.3 A floating beacon configuration

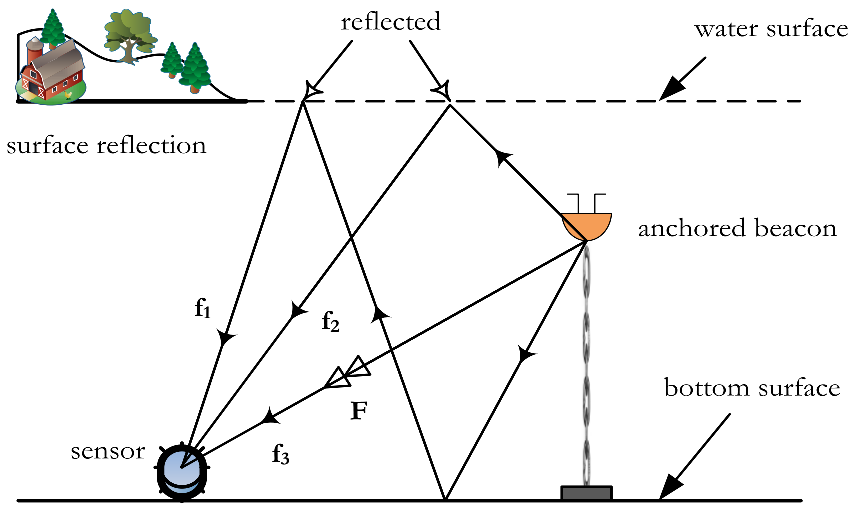

Fig. 4.4 A submerged beacon configuration

But in our model, the multipath fading phenomenon has close to none impact because it uses arrival time difference of radio and acoustic signals. Even though the radio signals does not propagate as of acoustic signals in underwater, but the right frequency of radio signals will give certain distance of propagation. The tremendous speed of radio signals compared to that of acoustic has been used for timing purposes. Section 3 has elaborated on the mechanism in details.

Perhaps the most distinguishing property of acoustic channels is the fact that path loss depends on the signal frequency [156]. This dependence is a consequence of absorption, i.e. transfer of acoustic energy into heat. In addition to the absorption loss, signal experiences a spreading loss which increases with distance. The overall path loss is given as follows.

$$A(l, f) = (l/l_r)^k a(f)^{l-l_r} \tag{4.1}$$

where f is the signal frequency, and l is the transmission distance, taken in reference to some l_r, The path loss exponent k models the spreading loss, and its usual values are between 1 and 2 (for cylindrical and spherical spreading, respectively). The absorption coefficient $a(f)$ is an increasing function of frequency, which can be obtained using an empirical formula [157]. It may be interesting to note that $10\log(a(f)) \approx \alpha_0 + \alpha_1 f + \alpha_2 f^2$ for frequency up to about 50kHz.

Surface reflection coefficient equals -1 under ideal conditions, while bottom reflection coefficients depend on the type of bottom (hard, soft) and the grazing angle [158]. If we denote the cumulative reflection coefficient along the p^{th}propagation path by τ_p and the propagation loss associated with this path by A_p, then $h_p = \tau_p/\sqrt{A_p}$ represents the gain of this path. At this point, we may be tempted to express the channel response as following as it is usually done for a radio channel [159].

$$h(t) = \sum_p h_p \delta(t - \tau_p) \tag{4.2}$$

The path gain in an acoustic channel is a function of frequency. Hence, it is constant only for a single frequency signal, i.e. a tone. For a broadband signal, each frequency will experience a different attenuation. Using the attenuation, we obtain the frequency response of the p^{th} path.

$$H_p(f) = \frac{\tau_p}{\sqrt{A(l_p, f)}} \tag{4.3}$$

Hence, each path of an acoustic channel acts as a low-pass filter, introducing its own dispersion. Path dispersion is much less than the combined multipath spread of all paths, but a complete model must account for it nonetheless. Any approximations that may result from the general model will depend on the spectral occupancy of the signal. The overall channel response in the frequency domain is

$$H(f) = \sum_{p} H_p(f) e^{-j2\pi f \tau_p} \tag{4.4}$$

and the corresponding impulse response can be expressed as

$$h(t) = \sum_{p} h_p(t - \tau_p) \tag{4.5}$$

where $h_p(t)$ is the inverse Fourier transform of $H_p(f)$. The total multipath spread is governed by the longest path delay, which is on the order of tens of milliseconds [156]. All these effect of multipath can be avoided using radio and acoustic signals for distance estimation.

4.4 Proposed Algorithm

An algorithm to determine the distance between beacon and submerged sensors has been depicted here. Both radio and acoustic signals have been used to eliminate the impact of multipath fading as well as to measure average acoustic speed for a vertical water column precisely.

4.4.1 Distance Measurement Technique

Assumptions:

- The beacon can generate radio and acoustic signals at the same time.
- Deployed sensors can receive radio signals only (no need of radio transmission by the sensors as it would consume lot of power), but would be able to generate and receive acoustic signals.
- Acoustic signals will be used for communications.
- The environmental factors that affect the acoustic signals will be considered while measuring inter-node distances.
- Sensor nodes are stationary during the short measurement period.

- Beacon (boat or buoy - at the water level) and sensor nodes (at the bottom) are in parallel or non-parallel state.
- Each sensor will have a unique ID.

Steps:

1. Simultaneous generation of radio and acoustic signals by beacon $S_j, j = 4,5, ...$ at t_0 (here, S_j:different positions of beacon in the same water level)
2. For any submerged sensors $S_i, i = 1,2,3$
   a. Sensors receive the radio signals immediately at $t_{Ra(rec)} = t_0 + \varepsilon$ (ε: travelling time of radio signals from the beacon to the sensors)
   b. Sensor receives the acoustic signals after a while at $t_{Ac(rec)}$;
   here, $t_{Ac(rec)} - t_0 \gg t_{Ra(rec)} - t_0$ due to speed of radio signals (2.25×10^{6}m/s).
3. Time of acoustic signals travelled from beacon to sensors:

$$T_{ij(travel),i=1,2,3;j=4,5,6....} = t_{Ac(rec)} - t_{Ac(tra)} = t_{Ac(rec)} - t_{Ra(tra)}$$

$$\because t_{Ac(tra)} = t_{Ra(tra)}$$

$$\therefore T_{ij(travel)} \approx t_{Ac(rec)} - t_{Ra(rec)} \quad \because t_{Ra(rec)} = t_0 + \varepsilon \approx t_{Ra(tra)}$$

4. Sensor nodes send back the time $T_{ij(travel)}$ with individual sensor's ID back to the beacon using acoustic signals.
5. Beacon node computes the distance between the beacon and sensors:

$$d_{ij} = v_A \times T_{ij(travel)},$$

   here, v_A is average speed of acoustic signals for the water column.

Fig 4.5 shows the sequence of message transfer between the beacon and underwater sensor with the time frame. As beacon would generate both radio and acoustic signals at the same time, the radio would be received by the sensors immediately. In theory ε amount of time would be required, which is negligible for radio signals to cover only ~200m apart sensors. Compared to radio acoustic signal will be received after a substantial amount of time late, by timing the radio and acoustic signals received by the sensors flight time of the acoustic signal from beacon to sensors could be calculated. This recorded time with specific sensor's ID along with other parameters that affect underwater acoustic speed will be sent to the beacon at the surface for further calculations. All the calculations from average acoustic speed to coordinates determination will be carried out at the beacon (boat) as it has unlimited power supply. The whole procedure of determining the flight time would take small amount of time such that even involuntary mobility of the sensor would have minimal effect.

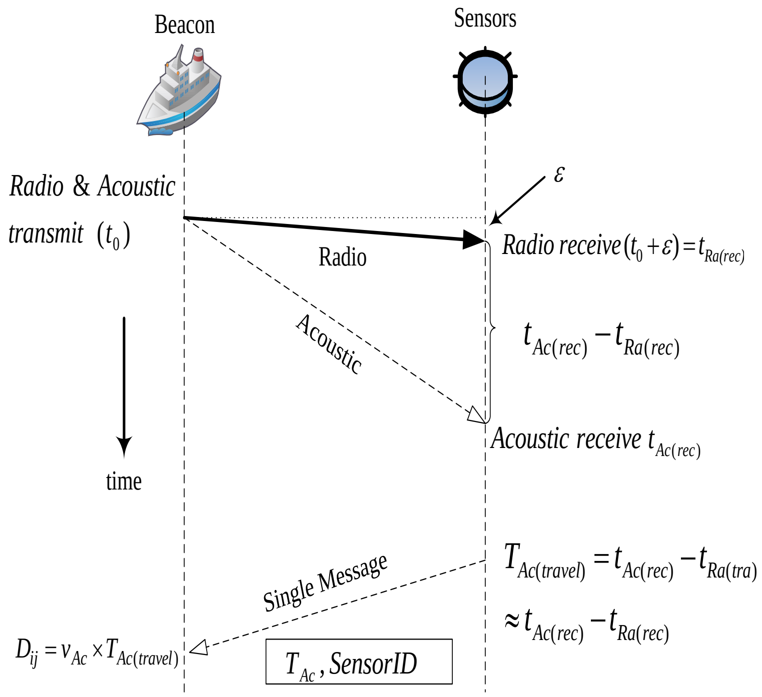

Fig. 4.5 Message transmission for distance calculation

Flow Chart of the Algorithm:

Following Fig. 4.6 is the flow chart that expresses the sequence of action taken by individual device to measure distances between beacon at the surface and deployed underwater sensors. It also shows the actions to be taken in cases of malfunctions when signals would not reach or detected by the sensors. Action will be taken depending on the time limit, and this time limit will be set according to the depth of the problem domain. All the actions at the first row belong to the beacon, and rest of them belong to the underwater sensor. All computation will take place at the beacon (a boat) which has abundance of power supply, so that sensors with limited power will last longer.

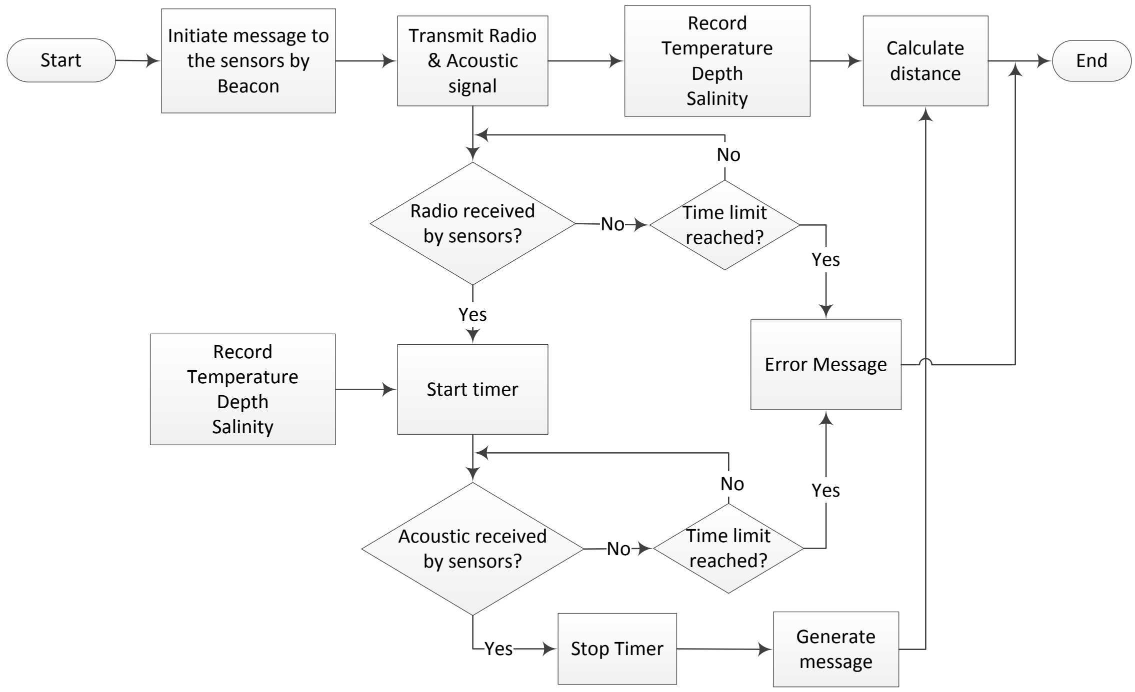

Fig. 4.6 Flow chart of distance determination with radio and acoustic signals

The whole algorithm will start by initiating a message to the sensors, this message can wake all the sensors up to get into a 'localization process about to begin' state. The message could contain related information like the frequency of the signals will be used, time limit that the sensors should use before generating error message and instruction to record environmental variable i.e., temperature, pressure and salinity. After the initial process beacon would transmit both radio and acoustic signals in predefined frequencies; as soon as the radio signals are received by the underwater sensors, a timer will start and will stop once the acoustic signals are received. As underwater environment is often noisy this form of preselected frequency will help sensors not to be mistaken with other signals present underwater. Preset time limit will also help when to generate error message; the duration of time limit (threshold) should be lower than it takes to travel twice the depth of problem domain approximately. Same phenomenon has been used in the experiment in Ch. 6 for 50cm problem domain taking 1450μs as threshold. This contention period will help sensors to avoid receiving bounced signals from the surface or nearby objects. Once the timing of acoustic signal is measured, the information will be send to the beacon by an acoustic message along with measured environmental variables for distance calculation. This way multipath effect could be avoided in *in-situ* distance determination.

4.4.2 Average Underwater Acoustic Speed Calculation

A typical speed of acoustic waves near the ocean surface is about 1500m/s, more than four times faster than the speed of sound in air. However, the speed of sound in underwater is affected prominently by temperature, salinity and depth. As these parameters are variable and different from place to place in the water; so as the speed. The speed of acoustic signal v in water can be calculated according to the Mackenzie Eq. (2.2). Mackenzie equation gives sound speed for any specific value of $\mathtt{T}$, $\mathtt{D}$ and $\mathtt{S}$ whereas for our problem domain we need average speed of sound through the water column where all three variables change dynamically. It should be noted that in shallow water temperature predominates whereas depth and salinity have very minimal effect on sound speed as we can see in simulation. Here, the pressure at the bottom by the sensors will be converted to depth $\mathtt{D}$ following equation stated in [160].

Following Mackenzie equation, the variable sound speed can be portrayed according to the Fig. 4.7 that shows the sound speed for any particular point.

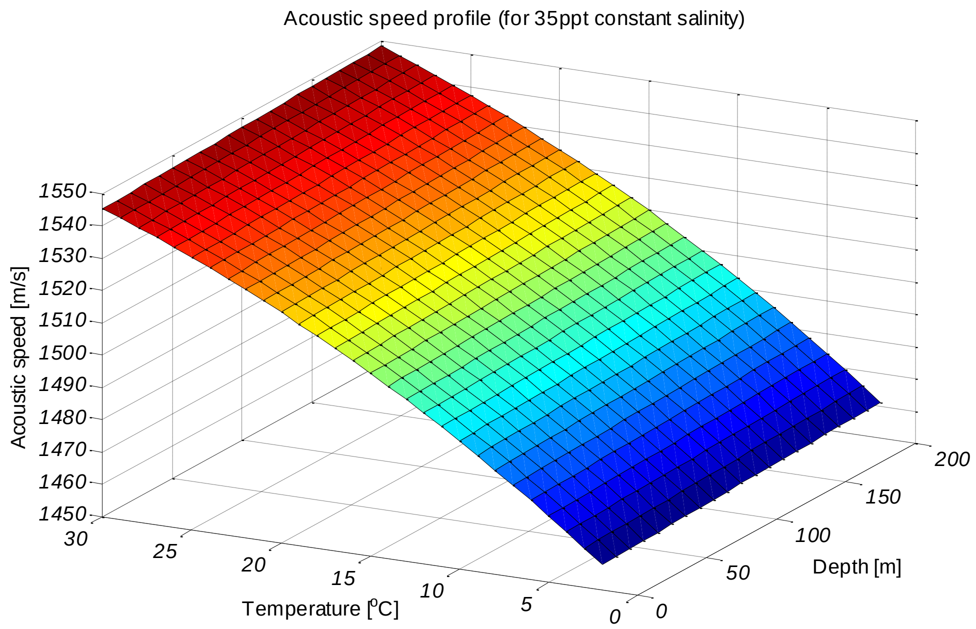

Fig. 4.7 Acoustic speed profile according to Mackenzie equation

For our problem domain it is necessary to find the average sound speed that travels from beacon to the sensors for a particular water column. With some data of the water column we propose equation to define average sound speed. Our proposed average speed of sound for the problem domain can be calculated with Eq. (4.6).

$$\bar{v} = f_{avg}(T,D,S) = \frac{1}{A}\iiint_R f(T,D,S)dA = \frac{1}{A}\int_{S_i}^{S_f}\int_{0}^{D_f}\int_{T_i}^{T_f} f(T,D,S)dTdDdS \tag{4.6}$$

here, A is area created by the limit of T, D and S: temperature, depth and salinity respectively, $f(T,D,S)$ is Mackenzie equation.

Derivative of multivariate Mackenzie equation [35] is used to compute average speed of acoustic signals from beacon to sensors instead of considering 1500m/s as most localization methods do. Simulation for average acoustic determination is done for various water columns with different combinations of parameters. For example Fig. 4.8 shows average acoustic speed for 200m water column with 20ºC surface and 10ºC bottom temperature having salinity variation of 0.5ppt from beacon to sensors. We have incorporated Gaussian noise (μ=0, σ=1) to 10ºC bottom temperature and to the flight time as both of them have more uncertainties than the measured surface temperature. Mean of 'average sound speed' is found to be 1507.6m/s for 100 iterations with standard deviation 1.97. Results suggest the model has better immunity from multipath fading and capable of producing *in-situ* results.

4.5 Complexity of Distance Measurement

Being aware of the limitations of radio and acoustic signals in water, each of its merit has been used in our proposed method to determine the distances in the problem domain. Followings are explanation of complexity level of few important issues how

4.5.1 Equipped Hardware

The method is relatively simple but precise enough when both the beacon and sensors are capable of transmitting/receiving radio and acoustic signals. To be precise, the beacon should be capable of acoustic (transmit (T_x) & receive(R_x)) and radio (transmit(T_x)) only. On the other hand, sensors should be capable of acoustic (transmit (T_x) & receive(R_x)) and radio (receive(R_x)) only. Considering most of the practical applications, this assumption is considered pragmatic and possible to incorporate these featured with the sensors. In our approach, we propose to synchronize the clocks of beacon and sensors for flight time of acoustic signals with radio signals, which in turns gives better accuracy in distance measurements. Moreover, we propose to calculate average *in-situ* acoustic speed from the nodes ambient variables which also helps to generate better accuracy in localization for a dynamic problem domain.

Furthermore, our model has very low overhead. Fig. 4.5 shows the sequence of action that each node performs; where at the end only one message with the value of $T_{ij(travel)}$ and sensor ID is transferred via acoustic signals from sensor to beacon for distance calculation.

4.5.2 Variables (Temp., Depth, Salinity) Measurements

It has become a norm nowadays to incorporate multiple sensors within a node. In our model we propose to measure distances between beacon and underwater sensors by calculating *in-situ* average acoustic speed. To do such we are required to know the temperature, depth and salinity measurements at the vicinity of both the beacon and deployed sensors. To measure variables around beacon is comparatively much easier and accurate than to measure around underwater sensor nodes because of accessibility, maintenance and abundance of power supply; whereas we need to rely on the incorporated sensors without knowing its present condition. Moreover due to limited power and number of sensors in a node, sometimes low end sensors are incorporated, which eventually becomes more error prone. Hence the Gaussian noise is applied to the underwater measurements only while simulation. To determine the temperature and salinity conventional sensors will be used, on the other hand to determine depth of the node we propose use pressure sensors. Once the message is send back to the beacon with all the information, pressure readings will be converted into depth according to the following equations.

$$D = D_s(P, \emptyset) + \frac{\Delta\delta}{9.8} \tag{4.7}$$

which is obtained by solving the following hydrostatic equation:

$$\int_0^D gD\emptyset dD = \int_0^P V_{TSP}\, dP \tag{4.8}$$

here, $D_s(P, \emptyset)$ is a universal expression giving depth in what is call by oceanographers the "standard ocean" (an ideal medium in temperature and salinity with $T = 0^o\,C$ and S= $35\,ppt$), P is pressure and $\emptyset$ is latitude.

The term δ called the geopotential anomaly, accounts for the difference in temperature and salinity structure from the standard ocean. The complete formulation is following which converts pressure into depth depending on specific position of the earth.

$$D_s = \frac{9.7266 \times 10^2 P - 2.512 \times 10^{-1} P^2 + 2.279 \times 10^{-4} P^3 - 1.82 \times 10^{-7} P^4}{g(\emptyset) + 1.092 \times 10^{-4} P} \tag{4.9}$$

where $g(\emptyset)$ is given by the international formula for gravity

$$g(\emptyset) = 9.780318(1 + 5.2788 \times 10^{-3} sin^2\emptyset - 2.36 \times 10^{-5} sin^4\emptyset) \tag{4.10}$$

As devised in [155] Eq. (4.9) gives departures smaller than $\pm 0.03\ m$ in all situations.

4.6 Simulation and Analysis

This section gives the simulation results and analyses how environmental variables affect acoustic speed for a vertical water column. It is well established that temperature, depth and salinity are the three variables that effect underwater acoustic speed; in this section we have analyzed the result of average acoustic speed for a vertical water column and compared the effect of different variables on acoustic speed.

4.6.1 Analysis

Our distance measurement technique is unique for underwater localization where both acoustic and radio signals is used. Despite propagation limitation of radio signals, we have tactically chosen to serve our purpose because radio signals can propagate up to 1.8-323m with an approximate speed of 2.25x10^6m/s [20]. By using this tremendous speed we can measure the flight time of acoustic signals from beacon to sensors precisely; moreover, with a single message exchange beacon node will come to know the flight time as well as other variables associated at the sensors. Hence, average sound speed determination procedure incorporates on-site values of variables that will incorporate less error in inter nodes distance measurements.

In this approach of coordinate determination multipath fading will have minimal impact. The sensors are only detecting the presence of signals instead of accessing its strength; as soon as the shortest Euclidean distance is travelled - signal can be detected and timed. Hence, the obvious notion of multipath fading in the radio and acoustic signals propagation will not affect timing in our method. With this, the precise acoustic velocity would give an accurate distance measurement resulting in coordinates estimates with less error. Simulation results in section 5.3 suggest that with true Euclidean distances our method determines coordinates of the sensors with negligible error.

4.6.2 Calculation of Average Sound Speed

Average sound speed is computed for 200m water column with 20°C surface and 10°C bottom temperature having salinity variation of 0.5ppt. Gaussian noise has been added (μ=0, σ=1) to 10°C bottom temperature as bottom temperature has more uncertainties in reading than surface temperature reading. Fig. 4.8 shows the variations in 'average sound speed' due to the aforesaid conditions for 100 iterations with standard deviation 1.97. Mean of 'average sound speed' is found to be 1507.6m/s for the aforesaid problem domain.

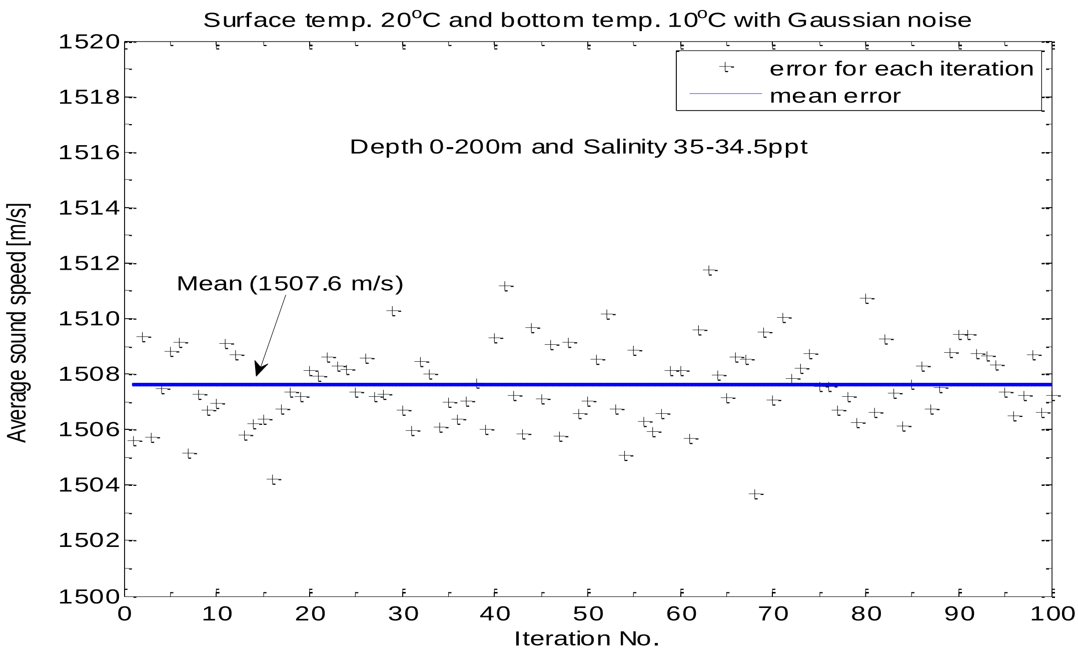

Fig. 4.8 Average speed with 20°C surface temp. for 200m water column

Fig. 4.9 also shows the average acoustic change if the surface temperature of water is considered 15^{o}C keeping all other factors same, i.e. bottom temperature 10^{o}C with incorporation of Gaussian noise for 200m water column and mean of 'average acoustic speed' is found to be 1499.8m/s.

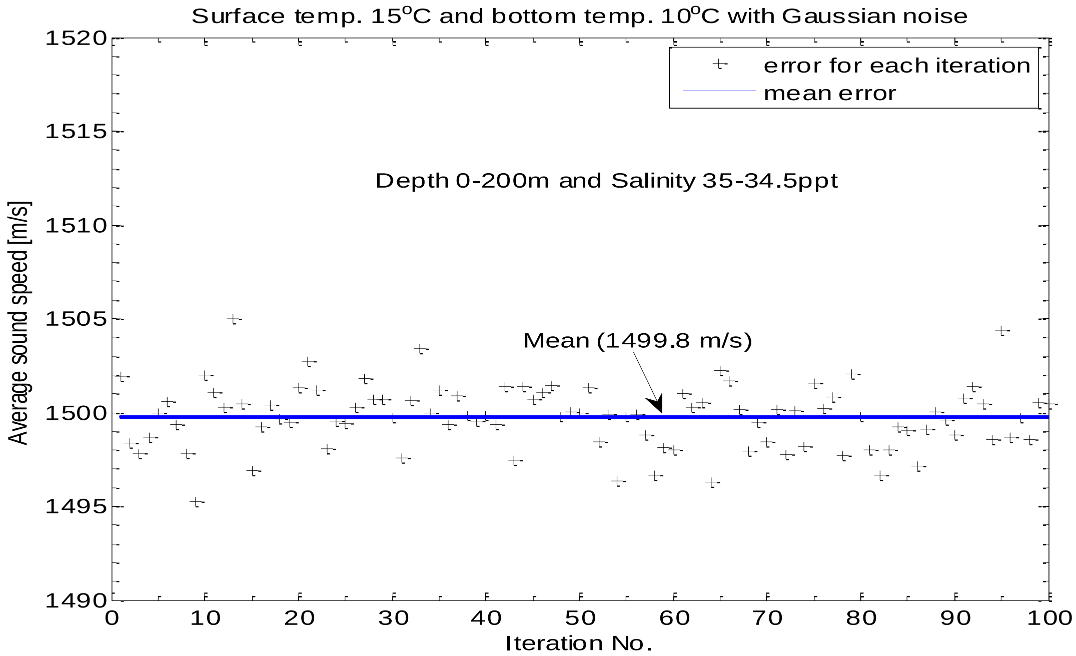

Fig. 4.9 Average speed with 15^{o}C surface temp. for 200m water column

Fig. 4.10 shows the speed is 1507.2m/s when the surface temperature is 20^{o}C for a 150m water column keeping all other factors same. From these results we can see that how the average acoustic speed changes due to the change of problem domain and variables. So, in-situ acoustic speed determination is vital for localization where problem domain is very dynamic.

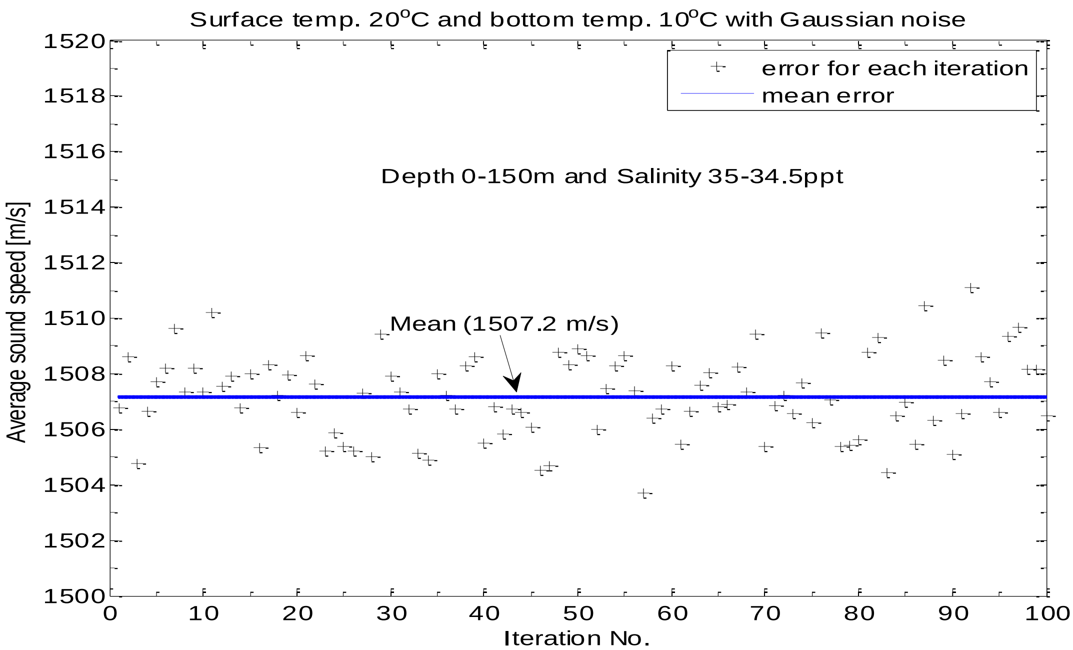

Fig. 4.10 Average speed with 20°C surface temp. for 150m water column

4.6.3 The Effect of Variables on Sound Speed in a Vertical Water Column

The deployed underwater sensor nodes to be localized by measuring the distances with acoustic signals' flight time from a surfaced beacon gives us a vertical water column to be analyzed. What factors and to what extent the variables effect the underwater sound speed is analyzed in this section. We have used Eq. (2.2) as a function in our proposed Eq. (4.6) and determined how sound speed varies due to what factors for our problem domain. Various situations have been simulated and analyzed to find the degree of variables' effect on average sound speed. Table 4.1 shows average speed of sound due to surface and bottom temperature chance.

Table 4.1 Average sound speed due to surface and bottom temperature change

		Surface Temperature		
		25°C	20°C	15°C
Bottom Temperature	20°C	1528.06m/s	-	-
	15°C	1521.03m/s	1514.06m/s	-
	10°C	1513.31m/s	1506.01m/s	1498.02m/s

In Fig. 4.11 the effect of temperature on average sound speed has been portrayed for a 200m depth problem domain having 0.5ppt salinity difference. Simulation has been performed with 15°C, 20°C, 25°C surface temperature and 2°C bottom temperature limit; average sound speed increases 7.3m/s due to change in surface temperature from 20°C to 25°C while bottom temperature is 10°C. For 5°C bottom temperature change with 20°C surface temperature average sound speed changes from 1514.06m/s to 1506.01m/s. For 20°C surface temperature, average sound speed increases 1.7m/s for only 1°C increase in bottom temperature. 0.53% change due to 5°C change at the bottom temperature is quite significant.

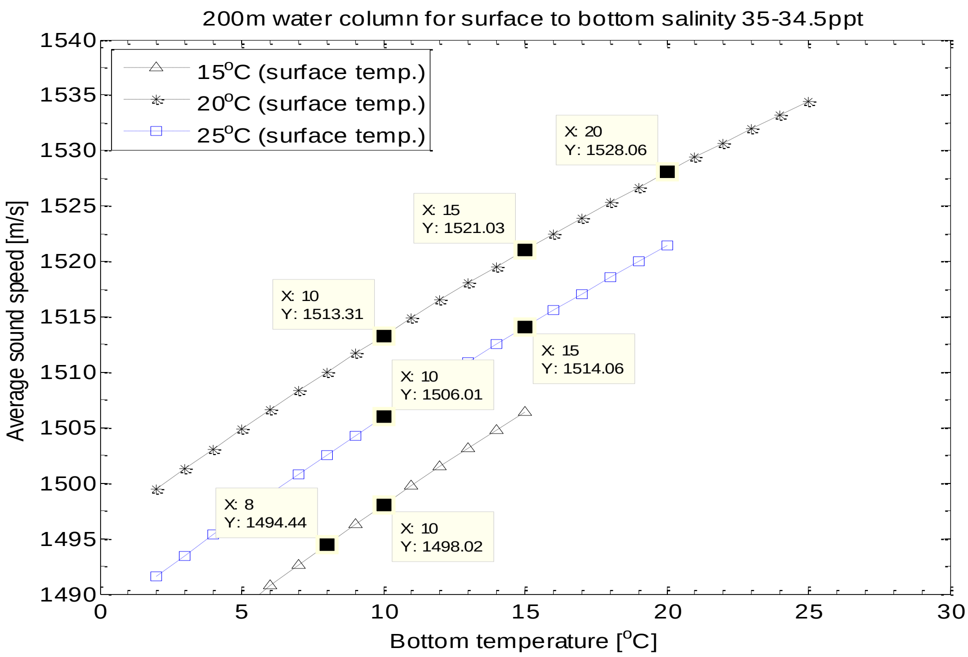

Fig. 4.11 Average sound speed for different surface and bottom temperature

Average sound speed changes due to depth of the problem domain change has also been simulated for different combination of surface and bottom temperature with 0.5ppt difference as depicted in Fig. 4.12. The result shows that sound speed change due to depth is not as significant as temperature which can be seen in Fig. 4.12 and 4.13. Due to change of the water column from 200m to 180m and 120m, the average speed only changes 0.17m/s and 0.66m/s respectfully. Whereas for 200m problem domain with 20°C surface temperature, if the bottom temperature changes from 10°C to 5°C sound speed changes 8.81m/s. Sound speed due to bottom temperature changes for various water column is shown in Table 4.2. From these results we can see that the temperature is the prominent variable for our problem domain that we should be concerned while measuring average sound speed. Average sound speed increases only 0.09m/s due to 10m increase in water column for the same condition as in Fig. 4.11. So, for 200m water column, 5% error in depth measurement can affect the average sound speed by 0.059% which is almost negligible.

Table 4.2 Average sound speed changes with 20°C surface temperature

		Bottom Temperature		
		15°C	10°C	5°C
Water Column	0 - 200m	1514.06m/s	1506.01m/s	1497.20m/s
	0 - 180m	1513.90m/s	1505.84m/s	1497.04m/s
	0 - 160m	1513.74m/s	1505.68m/s	1496.88m/s
	0 - 140m	1513.57m/s	1505.52m/s	1496.71m/s
	0 - 120m	1513.41m/s	1505.35m/s	1496.55m/s

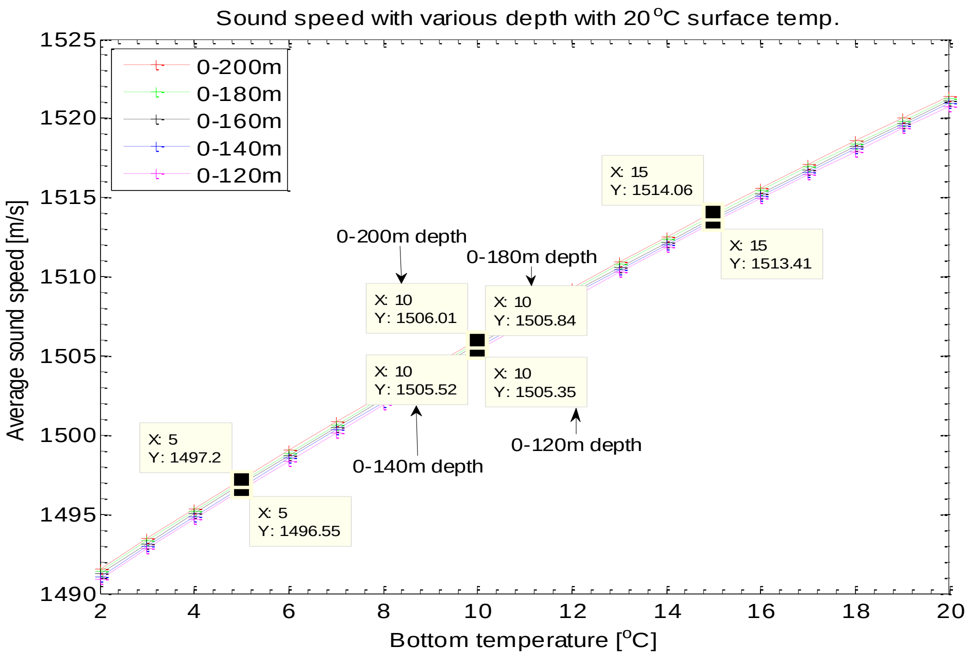

Fig. 4.12 Average sound speed for different depth with surface temperature 30°C

Average sound speed changes with different salinity variation between surface and the bottom of the 200m depth problem domain also been simulated for different combination of surface and bottom temperature. Fig. 4.14 and 4.15 show variations in sound speed changes for a 200m problem domain for different combinations of surface and bottom salinities with temperature variations. Table 4.3 shows increase in salinity variation decreases average speed for a certain temperature combination.

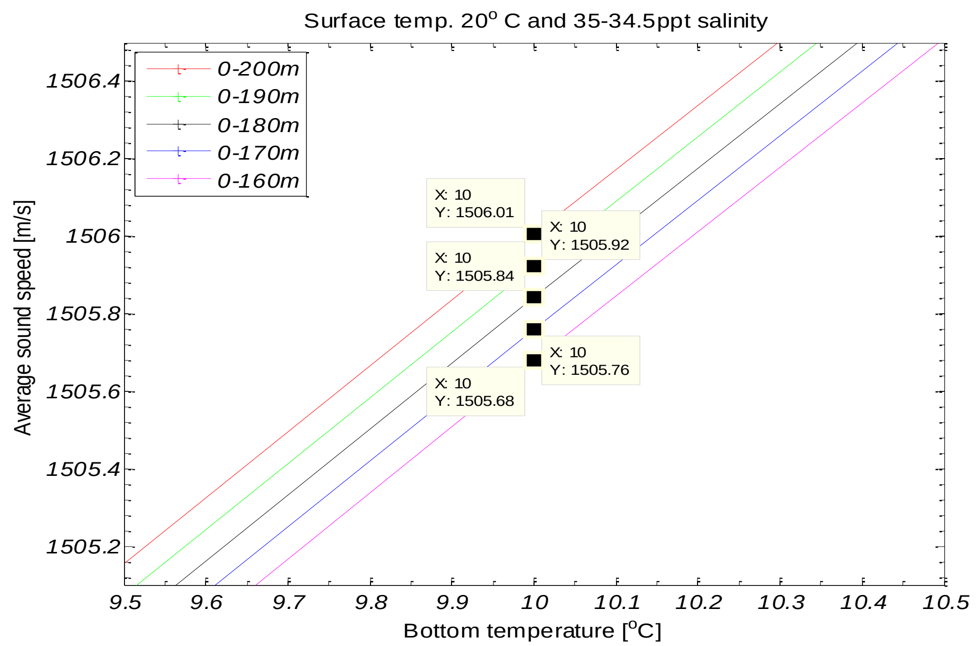

Fig. 4.13 Average sound speed for different depth with surface temperature 20°C

Table 4.3 Average sound speed changes with 20°C surface temperature

		Bottom Temperature		
		15°C	10°C	5°C
Salinity Variation	35.50 – 35.25ppt	1514.79m/s	1506.75m/s	1497.96m/s
	35.50 – 35.00ppt	1514.65m/s	1506.60m/s	1497.81m/s
	35.50 – 34.75ppt	1514.50m/s	1506.45m/s	1497.66m/s
	35.50 – 34.50ppt	1514.35m/s	1506.30m/s	1497.51m/s

Simulation results also suggest salinity increase affects average speed of sound positively; 0.14m/s increase of average sound speed due to 0.25ppt salinity change at the bottom surface. 0.029% increase in average sound speed for 0.75ppt salinity change at the bottom surface is not quite dramatic as it is the case in temperature change. Average sound speed changes due to salinity variation are even smaller than depth variations as shown in Fig. 4.14 and 4.15.

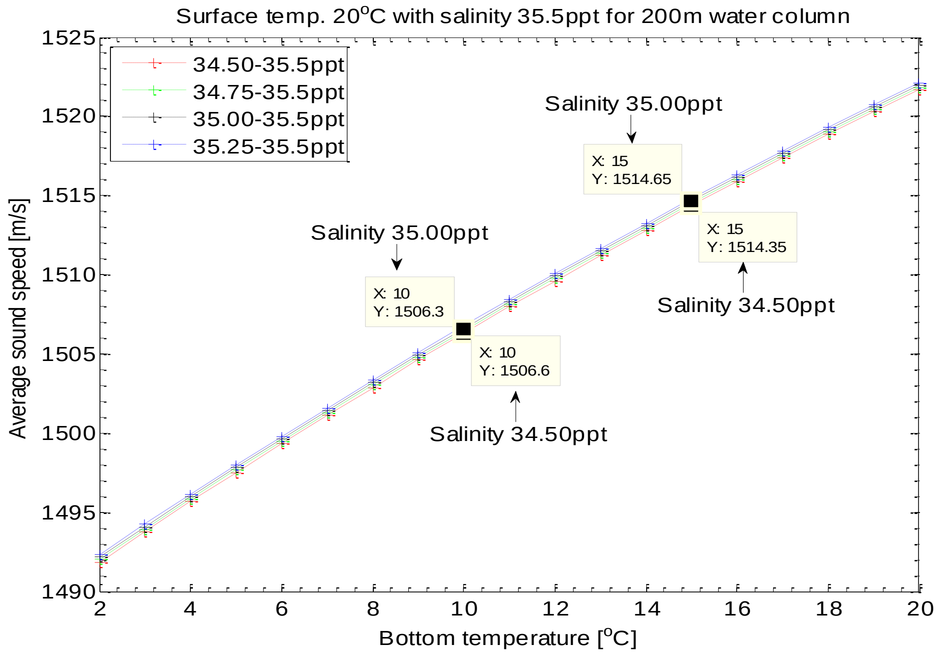

Fig. 4.14 Average sound speed for different salinity with surface temperature 20°C

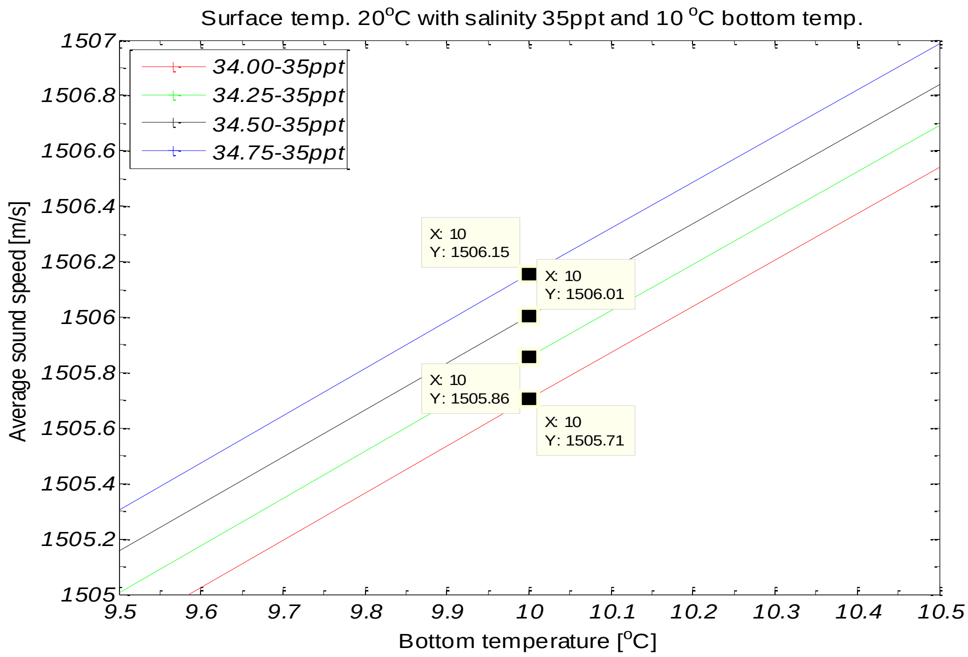

Fig. 4.15 Average sound speed for different salinity with surface temperature 20°C

From the above simulation results, it can be inferred that temperature is the prime factor to be considered to avoid possible errors in average sound speed for any shallow water column. In other words, errors in temperature measurements will affect more than depth and salinity in calculation of the average sound speed; in fact for 200m water column, depth and salinity effect on average sound speed is quite negligible. Due to this reason temperature measurement at the surface as well as at the bottom should be done precisely to keep coordinates error low. Instead of considering average underwater acoustic speed as 1500m/s, *in-situ* acoustic speed determination is vital for precise localization.

4.7 Conclusions

As distance determination is one of the main steps to coordinate determination, we tried to achieve it as error free as possible. From the beginning of proposing algorithm as well as determining the speed of acoustic signal were our focal points. Instead of assuming acoustic speed underwater we propose mechanism how to calculate average speed of acoustic signal from the gathered environmental variables for a vertical water column. We have also examined that average underwater acoustic speed is more susceptible to temperature difference between the beacon and sensors. Depending on the problem domain and the availability of the measurements of the environmental variables, it is possible to decide when one can be neglected or one becomes more prominent. If the problem domain is shallower, it is more likely that salinity difference between the beacon (surface) and sensors' area would be very less; so the salinity effect can be neglected if it is not readily available. Besides, to determine the distance between beacon and sensors we propose to use radio signal incorporation with acoustic signal; due to limited propagation of radio signal problem domain in some case will be limited within shallow water. It can be concluded that to achieve precise coordinates of the sensors, it is very important that the distance between beacon and sensors are determined as accurately as possible. The better the distances are achieved, the better the coordinates are determined.

Chapter 5

COORDINATES DETERMINATION

This chapter focuses on coordinates determination with a mobile single beacon; once *in-situ* distances are measured between the beacon and deployed sensors as elaborated in Chapter 4, we propose to determine the coordinates and bearing of the sensors with respect to the beacon by using Cayley-Menger determinant and solved the non-parallel state situation between the plane on which the beacon surfs (water surface) and the plane created by deployed sensors. The proposed mathematical model has been simulated to find localization accuracy considering Euclidean distances as well as after incorporating Gaussian noise with distance measurements. Later in section 5.3.3, different orientations of the beacon have been explored to determine the effect on coordinates of the underneath sensors.

5.1 Introduction

In recent years, researchers have shown fervent interest to explore and to exploit underwater localization schemes to fulfill the multitude of needs as the time demands. Precise coordinate of the sensors with respect to other sensors as well as with respect to the beacon is necessary to comprehend the validity of gathered data in underwater wireless sensor networks (UWSN); as data without the knowledge of its actual origin has limited value. Besides, coordinates determination is one of the major parts in underwater localization and various underwater applications have been researched. A plethora of techniques have been proposed to determine the coordinate of the sensors; some are done with the assistance of mobile sensors, some are done with the help of multiple beacon nodes. However, traditional monitoring systems are expensive and complicated as most of them use preinstalled reference points [161]. Moreover, mostly multilateration technique is used to determine the location of the sensors with respect to three or more known beacon nodes and incorporated nonlinear distance equations are solved in conventional method where degree-of-freedom does not guarantee a unique solution. Conversely, in our range-based solution Cayley-Menger determinant and linearized trilateration are used to determine the coordinates of the nodes where none of nodes have *a priori* knowledge about its location.

A pragmatic dynamic approach has been propounded here to localize submerged nodes with minimal logistics. Our proposed technique is as pragmatic as possible, where only a single beacon (boat/buoy) at the surface will be used to determine the coordinates of multiple underwater deployed sensors. The associated 'parallel state' limitation with Cayley-Menger determinant has been solved and a mathematical model has been developed and validated by simulation in this chapter.

5.2 Proposed Technique

The objective of localization algorithms is to obtain the coordinates of all the sensors. Only values available here to compute is the distance measurements as computed in Chapter 4 and typically it is considered as optimization problem where objective functions to be minimized have residuals of the distance equations [49]. The variables of any localization problem is the coordinates of the nodes; in principle more distance equations than number of variables are required to solve this kind of problem. However, this approach known as degree-of-freedom analysis may not guarantee the unique solution in a nonlinear system.

Trilateration or multilateration techniques are nonlinear systems usually used to determine location or coordinates of the sensors in partial or full. According to Guevara et al. [162] the convergence of optimization algorithms and Bayesian methods depend heavily on initial conditions used and they circumvent the convergence problem by linearizing the trilateration equations. Fig. 5.1 gives a scenario for which the coordinates are determined in the following section. The figure consists of three submerged sensors and a single mobile beacon (boat) at the surface of the water. The plane $\Pi_{sensors}$ created by the three sensors S_1, S_2 and S_3 and the plane Π_{beacon} on which beacon roam around could be in two situations, i.e., parallel or non-parallel. Parallel state situation arises when underwater nodes like AUVs or UUVs are deployed and cruise maintaining a specific depth for certain operations. On the other hand, if the deployed sensors float randomly or set on the ground, it is more likely planes $\Pi_{sensors}$ and Π_{beacon} are not in parallel states, the states of parallel or non-parallel can be identified from the depth measurements of the sensors. It is convenient to incorporate all the sensors or nodes with a pressure sensor on board, and from the pressure reading depth of the nodes will be calculated as discussed in section 4.5.2. Solutions for the both scenarios are devised in the following subsequent sections.

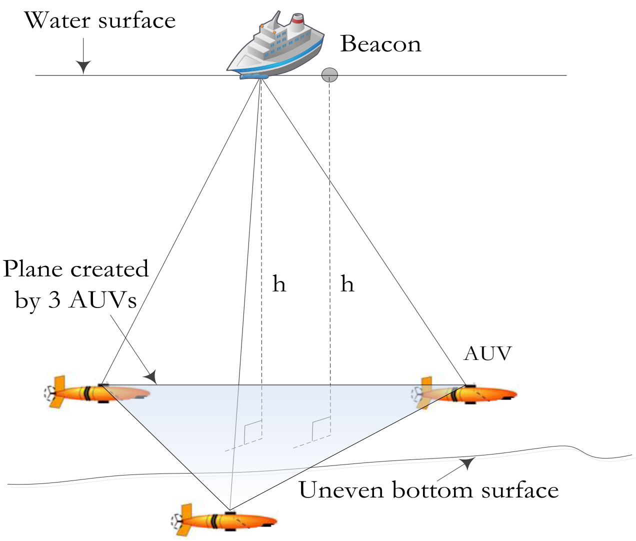

Fig. 5.1 Parallel states scenario

5.2.1 Coordinates of the Sensors

Fig. 5.2 shows the initial subset composed of the beacon node $S_j, j = 4,5\ldots9,$ and three sensor nodes $S_i, i = 1,2,3$. Without loss of generality, a coordinate system can be defined using one of the sensor nodes $S_i, i = 1,2,3,$ as the origin $(0,0,0)$ of the coordinate system. Now the trilateration equations can be written as a function of two groups of distance measurements: the distance between beacon and sensors $d_{14}, d_{24}, d_{34}\ldots$ which are measured data (known), and inter-sensor distances d_{12}, d_{13}, d_{23} and the volume of tetrahedron V_t (here, t is tetrahedron formed by the beacon and three deployed sensors), which are unknown.

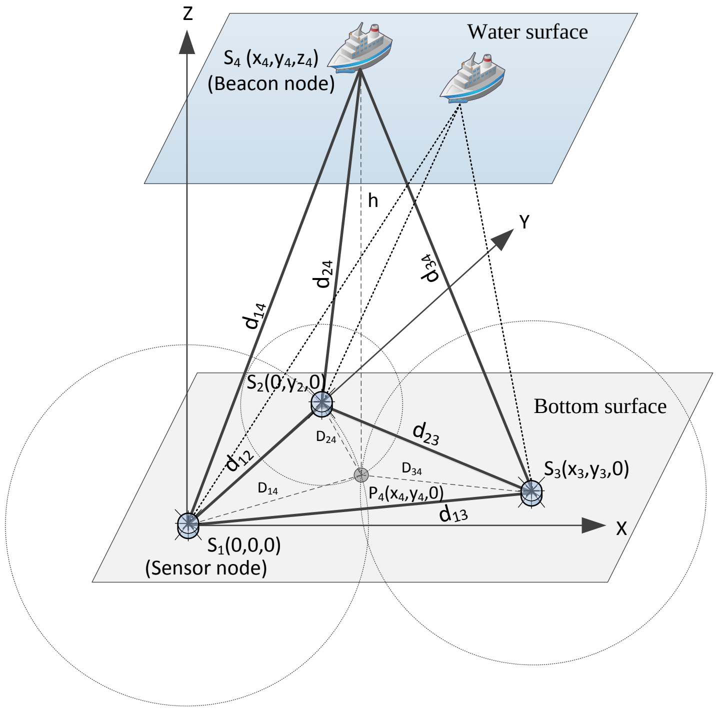

Fig. 5.2 Subset of three sensors and a mobile beacon for coordinates determination

Based on the local positioning system (LPS) configuration of Fig. 5.2, we need to write equation that will includes all known and unknown distances. For that matter, we express the volume of tetrahedron V_t using Cayley-Menger determinant as following:

$$288V_t^2 = \begin{vmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & d_{12}^2 & d_{13}^2 & d_{14}^2 \\ 1 & d_{12}^2 & 0 & d_{23}^2 & d_{24}^2 \\ 1 & d_{13}^2 & d_{23}^2 & 0 & d_{34}^2 \\ 1 & d_{14}^2 & d_{24}^2 & d_{34}^2 & 0 \end{vmatrix} \tag{5.1}$$

By expanding equation 5.1, we get

$$d_{34}^2 d_{23}^2 - d_{34}^2 d_{12}^2 + d_{34}^2 d_{13}^2 - \frac{d_{14}^2 d_{23}^4}{d_{12}^2} + d_{23}^2 d_{14}^2 + \frac{d_{13}^2 d_{14}^2 d_{23}^2}{d_{12}^2} - \frac{d_{24}^2 d_{13}^4}{d_{12}^2} + \frac{d_{13}^2 d_{23}^2 d_{24}^2}{d_{12}^2} + d_{13}^2 d_{24}^2 - d_{13}^2 d_{23}^2$$
$$-144\frac{V_t^2}{d_{12}^2} + \frac{d_{14}^2 d_{23}^2 d_{24}^2}{d_{12}^2} + \frac{d_{14}^2 d_{23}^2 d_{34}^2}{d_{12}^2} - \frac{d_{23}^2 d_{24}^2 d_{34}^2}{d_{12}^2} - \frac{d_{14}^4 d_{23}^2}{d_{12}^2} + \frac{d_{13}^2 d_{24}^2 d_{34}^2}{d_{12}^2} - \frac{d_{13}^2 d_{14}^2 d_{34}^2}{d_{12}^2} + \frac{d_{13}^2 d_{14}^2 d_{24}^2}{d_{12}^2} - \frac{d_{13}^2 d_{24}^4}{d_{12}^2}$$
$$-d_{34}^4 + d_{24}^2 d_{34}^2 + d_{14}^2 d_{34}^2 - d_{14}^2 d_{24}^2 = 0$$

Grouping known-unknown variables, we get

$$d_{34}^2\left(d_{12}^2-d_{23}^2-d_{13}^2\right)+d_{14}^2\left(\frac{d_{23}^4}{d_{12}^2}-d_{23}^2-\frac{d_{13}^2d_{23}^2}{d_{12}^2}\right)+d_{24}^2\left(\frac{d_{13}^4}{d_{12}^2}-\frac{d_{13}^2d_{23}^2}{d_{12}^2}-d_{13}^2\right)$$
$$-\left(d_{14}^2d_{24}^2+d_{14}^2d_{34}^2-d_{24}^2d_{34}^2-d_{14}^4\right)\frac{d_{23}^2}{d_{12}^2}-\left(d_{34}^2d_{24}^2-d_{14}^2d_{34}^2+d_{14}^2d_{24}^2-d_{24}^4\right)\frac{d_{13}^2}{d_{12}^2}$$
$$+\left(144\frac{V_t^2}{d_{12}^2}+d_{13}^2d_{23}^2\right)=\left(d_{24}^2d_{34}^2-d_{34}^4+d_{14}^2d_{34}^2-d_{14}^2d_{24}^2\right)$$

Rearranging the terms

$$d_{14}^2\left(\frac{d_{23}^4}{d_{12}^2}-d_{23}^2-\frac{d_{13}^2d_{23}^2}{d_{12}^2}\right)+d_{24}^2\left(\frac{d_{13}^4}{d_{12}^2}-\frac{d_{13}^2d_{23}^2}{d_{12}^2}-d_{13}^2\right)+d_{34}^2\left(d_{12}^2-d_{23}^2-d_{13}^2\right)$$
$$-\left(d_{14}^2d_{24}^2+d_{14}^2d_{34}^2-d_{24}^2d_{34}^2-d_{14}^4\right)\frac{d_{23}^2}{d_{12}^2}-\left(d_{34}^2d_{24}^2-d_{14}^2d_{34}^2+d_{14}^2d_{24}^2-d_{24}^4\right)\frac{d_{13}^2}{d_{12}^2}+\left(144\frac{V_t^2}{d_{12}^2}+d_{13}^2d_{23}^2\right)$$
$$=\left(d_{24}^2-d_{34}^4\right)\left(d_{34}^2-d_{14}^2\right)$$

here,

$\left(\frac{d_{23}^4}{d_{12}^2}-d_{23}^2-\frac{d_{13}^2d_{23}^2}{d_{12}^2}\right)$, $\left(\frac{d_{13}^4}{d_{12}^2}-\frac{d_{13}^2d_{23}^2}{d_{12}^2}-d_{13}^2\right)$, $\left(d_{12}^2-d_{23}^2-d_{13}^2\right)$, $\frac{d_{23}^2}{d_{12}^2}$, $\frac{d_{13}^2}{d_{12}^2}$, and $\left(144\frac{V_t^2}{d_{12}^2}+d_{13}^2d_{23}^2\right)$

are unknown terms.

The above expansion can be rewritten as following:

$$d_{14}^2X_1+d_{24}^2X_2+d_{34}^2X_3-\left(d_{14}^2-d_{34}^2\right)\left(d_{24}^2-d_{14}^2\right)X_4-\left(d_{24}^2-d_{14}^2\right)\left(d_{34}^2-d_{24}^2\right)X_5+X_6$$
$$=\left(d_{24}^2-d_{34}^2\right)\left(d_{34}^2-d_{14}^2\right) \tag{5.2}$$

where,

$$\left(\frac{d_{23}^4}{d_{12}^2}-d_{23}^2-\frac{d_{13}^2d_{23}^2}{d_{12}^2}\right)=X_1$$

$$\left(\frac{d_{13}^4}{d_{12}^2}-\frac{d_{13}^2d_{23}^2}{d_{12}^2}-d_{13}^2\right)=X_2$$

$$\left(d_{12}^2-d_{23}^2-d_{13}^2\right)=X_3$$

$$\frac{d_{23}^2}{d_{12}^2}=X_4$$

$$\frac{d_{13}^2}{d_{12}^2}=X_5$$

$$\left(144\frac{V_t^2}{d_{12}^2}+d_{13}^2d_{23}^2\right)=X_6$$

which in fact resembles the following linear form:

$$a_1 x_1 + a_2 x_2 + \cdots + a_n x_n = b_1.$$

As we have six unknown in (5.2), we need at least six measurements, which could be done following the same procedure described earlier steering the beacon node $S_j, j = 4,5\ldots 9,$ in six different places and measuring the distances in the vicinity of S_4. Eventually we get a system of linear equations of the form

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1, \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2, \\ &\vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n &= b_m. \end{aligned} \tag{5.3}$$

If we omit reference to the variables, then system (5.3) can be represented by the array of all coefficients known as the augmented matrix of the system where the first row of the array represents the first linear equation and so on; that could be expressed in $AX = b$ linear form.

After doing so, for our system, we have

$$A = \begin{bmatrix} d_{14}^2 & d_{24}^2 & d_{34}^2 & -\left(d_{14}^2 - d_{34}^2\right)\left(d_{24}^2 - d_{14}^2\right) & -\left(d_{24}^2 - d_{14}^2\right)\left(d_{34}^2 - d_{24}^2\right) & 1 \\ d_{15}^2 & d_{25}^2 & d_{35}^2 & -\left(d_{15}^2 - d_{35}^2\right)\left(d_{25}^2 - d_{15}^2\right) & -\left(d_{25}^2 - d_{15}^2\right)\left(d_{35}^2 - d_{25}^2\right) & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{19}^2 & d_{29}^2 & d_{39}^2 & -\left(d_{19}^2 - d_{39}^2\right)\left(d_{29}^2 - d_{19}^2\right) & -\left(d_{29}^2 - d_{19}^2\right)\left(d_{39}^2 - d_{29}^2\right) & 1 \end{bmatrix},$$

$$X = \begin{bmatrix} \left(\frac{d_{23}^4}{d_{12}^2} - d_{23}^2 - \frac{d_{13}^2 d_{23}^2}{d_{12}^2}\right) \\ \left(\frac{d_{13}^4}{d_{12}^2} - \frac{d_{13}^2 d_{23}^2}{d_{12}^2} - d_{13}^2\right) \\ \left(d_{12}^2 - d_{23}^2 - d_{13}^2\right) \\ \frac{d_{23}^2}{d_{12}^2} \\ \frac{d_{13}^2}{d_{12}^2} \\ \left(144\frac{V_t^2}{d_{12}^2} + d_{13}^2 d_{23}^2\right) \end{bmatrix}, \qquad b = \begin{bmatrix} \left(d_{24}^2 - d_{34}^2\right)\left(d_{34}^2 - d_{14}^2\right) \\ \left(d_{25}^2 - d_{35}^2\right)\left(d_{35}^2 - d_{15}^2\right) \\ \vdots \\ \left(d_{29}^2 - d_{39}^2\right)\left(d_{29}^2 - d_{19}^2\right) \end{bmatrix}.$$

From the above representation, knowing X_1, X_2, X_3, X_4, X_5, and X_6 we calculate d_{12}, d_{13} and d_{23} as following:

$$d_{12}^2 = \frac{X_3}{(1 - X_4 - X_5)},\ d_{13}^2 = \frac{X_3 X_5}{(1 - X_4 - X_5)},\text{ and } d_{23}^2 = \frac{X_3 X_4}{(1 - X_4 - X_5)}.$$

If we let the coordinates of the submerged sensors S_1, S_2 and S_3 are $(0,0,0)$, $(0, y_2, 0)$ and $(x_3, y_3, 0)$ respectively, then according to Fig. 5.2, the inter-sensors distances could be written with respect to coordinates of the sensors as following:

$$d_{12}^2 = y_2^2,\ d_{13}^2 = x_3^2 + y_3^2,\text{ and } d_{23}^2 = x_3^2 + (y_2 - y_3)^2.$$

From the above values we get the unknown variables y_2, x_3 and y_3 computed as following:

$$y_2 = d_{12},\ y_3 = \frac{d_{12}^2 + d_{13}^2 - d_{23}^2}{2d_{12}},\ x_3 = \sqrt{\left(d_{13}^2 - \left(\frac{d_{12}^2 + d_{13}^2 - d_{23}^2}{2d_{12}}\right)^2\right)}$$

where d_{12}, d_{13} and d_{23} are computed distances. Table 5.1 summarizes the coordinates of the sensors for this system.

Table 5.1 Coordinates of the sensors with known measurements

Sensors	Coordinates
S_1	$(0,0,0)$
S_2	$(0, d_{12}, 0)$
S_3	$\left(\sqrt{\left(d_{13}^2 - \left(\frac{d_{12}^2 + d_{13}^2 - d_{23}^2}{2d_{12}}\right)^2\right)}, \frac{d_{12}^2 + d_{13}^2 - d_{23}^2}{2d_{12}}, 0\right)$

5.2.2 Coordinates of the Sensors with Respect to the Beacon

Until now we have been able to find the coordinates of the sensor nodes; to find the coordinate of the beacon node we follow the following steps:

After measuring the vertical distance h in between the beacon node $S_4(x_4, y_4, z_4)$ and the XY plane (plane of the sensor nodes) we can assume the projected coordinate of the beacon node $S_4(x_4, y_4, z_4)$ on the plane XY is $P_4(x_4, y_4, 0)$. To find x_4 and y_4, we can apply trilateration in the following manner assuming the distances between S_1, S_2, S_3 and P_4 are D_{14}, D_{24} and D_{34} respectively.

$$D_{14}^2 = x_4^2 + y_4^2, \tag{5.4}$$

$$D_{24}^2 = x_4^2 + (y_4 - y_2)^2, \tag{5.5}$$

$$D_{34}^2 = (x_4 - x_3)^2 + (y_4 - y_3)^2, \tag{5.6}$$

$$D_{14}^2 = d_{14}^2 - h^2, \tag{5.7}$$

$$D_{24}^2 = d_{24}^2 - h^2, \tag{5.8}$$

$$D_{34}^2 = d_{34}^2 - h^2. \tag{5.9}$$

From equation (5.4), (5.5) and (5.6) we obtain the projected beacon's coordinate $P_4(x_4, y_4, 0)$, here

$$x_4 = \frac{\sqrt{4d_{12}^2 D_{14}^2 - \left(D_{14}^2 - D_{24}^2 + d_{12}^2\right)^2}}{2d_{12}}, \qquad y_4 = \frac{1}{2d_{12}}\left(D_{14}^2 - D_{24}^2 + d_{12}^2\right).$$

As d_{14}, d_{24} and d_{34} are the hypotenuse of the $\Delta S_1P_4S_4$, $\Delta S_2P_4S_4$ and $\Delta S_3P_4S_4$ respectively, so it is possible to obtain D_{14}, D_{24} ,and D_{34} using Pythagorean Theorem, that is, D_{14}, D_{24}, and D_{34} are calculated by Eq. (5.7), (5.8), and (5.9) respectfully. So the coordinate of the beacon node $S_4(x_4, y_4, z_4)$ would be $S_4(x_4, y_4, h)$, where x_4, y_4, and h are known elements.

$$\therefore S_4(x_4, y_4, z_4) = S_4\left(\left(\frac{\sqrt{4d_{12}^2 D_{14}^2 - \left(D_{14}^2 - D_{24}^2 + d_{12}^2\right)^2}}{2d_{12}}\right), \left(\frac{1}{2d_{12}}\left(D_{14}^2 - D_{24}^2 + d_{12}^2\right)\right), h\right)$$

So if the origin of the Cartesian system is transferred on to the coordinate of the beacon node, then it is possible to find the coordinates of other sensors with respect to S_4, the beacon node. A linear transformation would give the results as in Table 5.2 in known values:

Table 5.2 Coordinates of the sensors with respect to beacon

Sensors	**Coordinates**
S_4	$(0,0,0)$
S_1	$(-x_4, -y_4, -z_4)$
S_2	$(-x_4, y_2 - y_4, -z_4)$
S_3	$(x_3 - x_4, y_3 - y_4, -z_4)$

Table 5.3 Coordinates of the sensors with known and computed values

Sensors	**Coordinates**
S_4	$(0,0,0)$
S_1	$\left(\frac{\sqrt{4d_{12}^2 D_{14}^2 - \left(D_{14}^2 - D_{24}^2 + d_{12}^2\right)^2}}{2d_{12}}, \quad -\frac{1}{2d_{12}}\left(D_{14}^2 - D_{24}^2 + d_{12}^2\right), \quad -h \right)$
S_2	$\left(\frac{\sqrt{4d_{12}^2 D_{14}^2 - \left(D_{14}^2 - D_{24}^2 + d_{12}^2\right)^2}}{2d_{12}}, \quad \frac{1}{2d_{12}}\left(d_{12}^2 - D_{14}^2 + D_{24}^2\right), \quad -h \right)$
S_3	$\left(\left(\sqrt{\left(d_{13}^2 - \left(\frac{d_{12}^2 + d_{13}^2 - d_{23}^2}{2d_{12}} \right)^2 \right)} - \frac{\sqrt{4d_{12}^2 D_{14}^2 - \left(D_{14}^2 - D_{24}^2 + d_{12}^2\right)^2}}{2d_{12}} \right), \quad \frac{1}{2d_{12}}\left(d_{13}^2 - d_{23}^2 - D_{14}^2 + D_{24}^2\right), \quad -h \right)$

5.2.3 Coordinates in Non-Parallel State Scenario

Previous section assumes the plane that is created by the three underwater sensors and the plane (water surface) on which the beacon surfs while taking distance measurements were thought to be in parallel state. In case of non-parallel plane situation, aforesaid mathematical model will be followed with additional adjustment as depicted in this section. Fig. 5.3 shows the scenario when planes

$$\Pi_{s_1,s_2,s_3}: (a_1x + b_1y + c_1z + \delta_1 = 0) \tag{5.10}$$

which is created by the underwater deployed sensors S_1, S_2, S_3 and the plane

$$\Pi_{beacon}: (a_2x + b_2y + c_2z + \delta_2 = 0) \tag{5.11}$$

which is where the beacon surfs around (water surface) are in non-parallel state.

The situation like in Fig. 5.3 would be more common in the real world scenario, unless if AUV/UUVs are used to maintain a specific depth as in Fig. 5.1 or if an artificial water container is used where the bottom surface is always parallel with the water surface. Regardless of the situation, if the depth of any of the sensors is different than the others we could conclude that both the planes are in non-parallel state.

The system of equations mentioned in section 5.2.1 is only valid if the planes are in parallel state; because the volume of multiple tetrahedrons created by three sensors and the multiple apexes (multiple beacons' positions) are equal. The variation in vertical distance will vary depending on the dihedral angle α as in equation (5.12) and variation can be minimized if the beacon's positions while measuring distances are in close proximity. As the proposed method requires six distance measurements from beacon to underwater sensors, the total process should be done in quicker fashion so that the mobility of the sensors will not feed in more errors in determined coordinates.

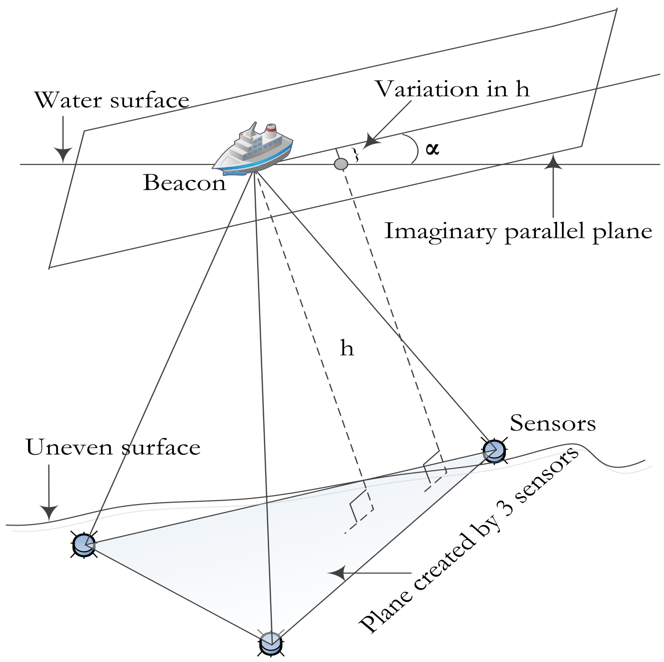

Fig. 5.3 Parallel planes effect

Depending on the accuracy, the surfing area of the beacon can be shortened which in turn produces less variation in the vertical distance.

$$\cos\alpha = \frac{\hat{n}_1.\hat{n}_2}{|\hat{n}_1||\hat{n}_2|} = \frac{a_1a_2 + b_1b_2 + c_1c_2}{\sqrt{a_1^2 + b_1^2 + c_1^2}\sqrt{a_2^2 + b_2^2 + c_2^2}} \tag{5.12}$$

where $\hat{n}_1 = (a_1, b_1, c_1)$ and $\hat{n}_2 = (a_2, b_2, c_2)$ are normal vector to the planes.

As mentioned earlier, all the deployed sensors or nodes will be equipped with a pressure sensor, which will read pressure. Once the pressure reading is sent to beacon, it will be converted in to depth following Eq. (4.9) and (4.10) as discussed in section 4.5.2. Once all the depth of the sensors is determined the following method could be applied to determine the coordinates as depicted in Fig. 5.4.

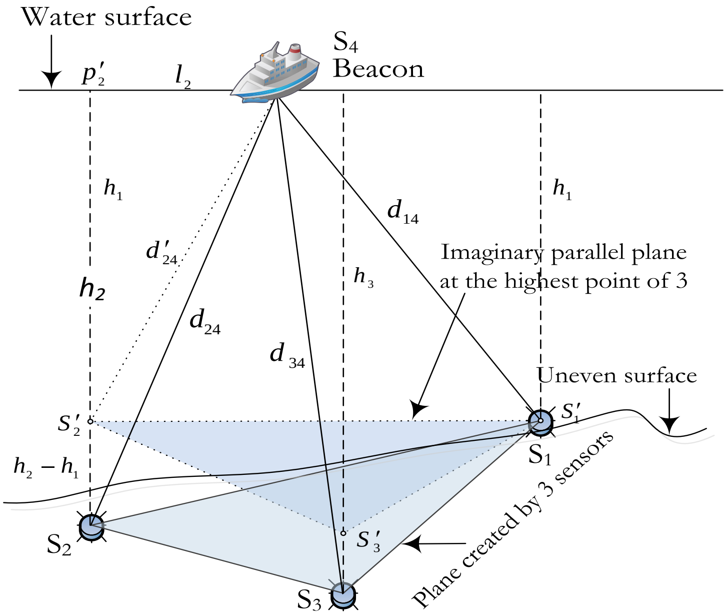

Fig. 5.4 Determination of coordinates - non-parallel state

Let the depths of the deployed sensors are h_1, h_2 and h_3 for the sensors S_1, S_2 and S_3 respectively, where assuming $h_3 > h_2 > h_1$, then S_1 is the highest point among all the three sensors with depth h_1. So the plane Π_{s_1,s_2,s_3} created by three points S_1, S_2 and S_3 would be in non-parallel state with the plane Π_{beacon}(water surface).

Let that highest point be S_1', where $S_1' = S_1$, we also imagine two more points S_2' and S_3' with depth same as h_1 right above S_2 and S_3 respectively. Since S_2' and S_3' are right above S_2 and S_3, x and y component of its coordinates will be same as S_2 and S_3 respectively, only z component of the coordinates will be different. So the plane $\Pi_{s_1's_2's_3'}$ and plane Π_{beacon} would be in parallel state. For $\Delta S_4 S_2 p_2'$, where p_2' is the projection of S_2, and d_{24} is the measured distance which would be taken according to the process discussed in Chapter 4; h_2 is measured depth from built-in pressure sensor associated with deployed nodes. So l_2, where l_2 is the distance between p_2' and S_4, can be calculated as:

$$l_2 = \sqrt{d_{24}^2 - h_2^2}. \tag{5.13}$$

Once l_2 is known, the imaginary distance d'_{24} can be achieved from the $\Delta S_4 S'_2 p'_2$

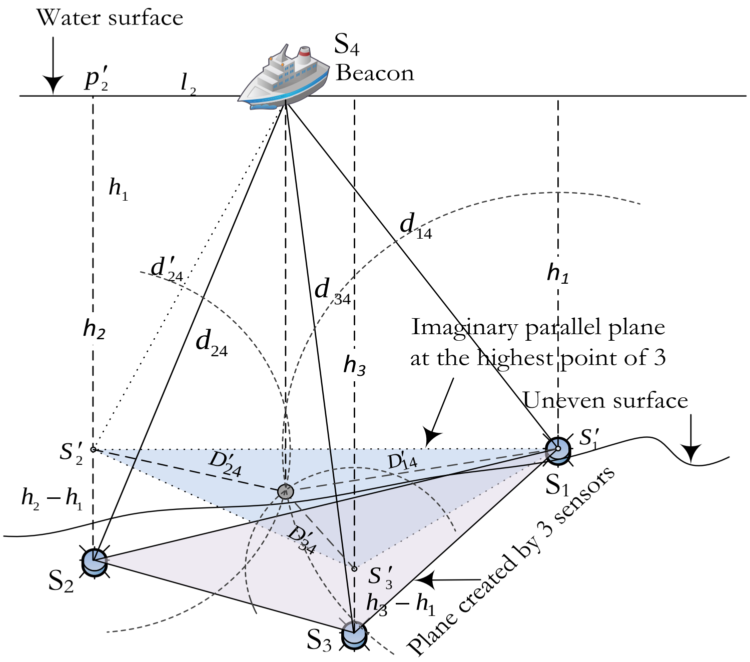

Fig. 5.5 Coordinates computation for non-parallel state

$$d'_{24} = \sqrt{l_2^2 + h_1^2}. \tag{5.14}$$

Same technique and procedure will be followed to find the distance between S_4 and imaginary point S'_3. Once all distances from beacon S_4 to imaginary points S'_2 and S'_3 are calculated, section 5.2.1 and section 5.2.2 will be followed to determine coordinates of S'_1, S'_2 and S'_3. Table 5.3 shows the determined coordinates of the sensors for parallel state with respect to the beacon S_4. Table 5.4 shows the computed coordinates of sensors S_1, S_2 and S_3 for non-parallel state.

Table 5.4 Coordinates of the sensors for non-parallel state

Sensors	Coordinates
S_4	$(0,0,0)$
S_1	$\left(\dfrac{\sqrt{4d_{12}^{'2}D_{14}^{'2}-\left(D_{14}^{'2}-D_{24}^{'2}+d_{12}^{'2}\right)^2}}{2d_{12}^{'}},\ -\dfrac{1}{2d_{12}^{'}}\left(D_{14}^{'2}-D_{24}^{'2}+d_{12}^{'2}\right),\ -h_1\right)$
S_2	$\left(\dfrac{\sqrt{4d_{12}^{'2}D_{14}^{'2}-\left(D_{14}^{'2}-D_{24}^{'2}+d_{12}^{'2}\right)^2}}{2d_{12}^{'}},\ \dfrac{1}{2d_{12}^{'}}\left(d_{12}^{'2}-D_{14}^{'2}+D_{24}^{'2}\right),\ -h_2\right)$
S_3	$\left(\left(\sqrt{\left(d_{13}^{'2}-\left(\dfrac{d_{12}^{'2}+d_{13}^{'2}-d_{23}^{'2}}{2d_{12}^{'}}\right)^2\right)}-\dfrac{\sqrt{4d_{12}^{'2}D_{14}^{'2}-\left(D_{14}^{'2}-D_{24}^{'2}+d_{12}^{'2}\right)^2}}{2d_{12}^{'}}\right),\ \dfrac{1}{2d_{12}^{'}}\left(d_{13}^{'2}-d_{23}^{'2}-D_{14}^{'2}+D_{24}^{'2}\right),\ -h_3\right)$

5.2.4 Bearing Determination

Bearing is an important piece of information that is required with the coordinates to comprehend the positions with global respect. The global position of the beacon is possible to know with GPS, which is very common and pragmatic in nature as most of the surface node (boat) is equipped with GPS. To determine bearings, coordinates of the sensors will be determined from two positions, namely B_1 and B_2 as in Fig. 5.6. Axis X or X' can be thought of as reference axis as directing north, so the angle θ can determine from the global position of B_1 and B_2. The line B_1 and B_2 creates an angle θ with the reference axis, which can be determined from the calculated coordinates of the sensors from the point B_1 and B_2. If the positions of B_2 are in the first quadrant of the Cartesian coordinates taking B_1 as the origin, then the computed θ would be positive and direction of positive X -axis would be usual as in Fig. 5.6. If position of B_2 is in second quadrant, θ would be negative and direction of positive x-axis would be opposite. Similarly if it is in third quadrant then θ is positive but direction of x-axis is opposite. If it is in forth quadrant then θ is negative but direction of positive x-axis would be as usual. We have tested keeping $\theta = 36^o$ and $\theta = 72^o$, and computed θ from the determined coordinates with Euclidean distances as well as with distances after incorporating Gaussian noise as in Table 5.5 - 5.8.

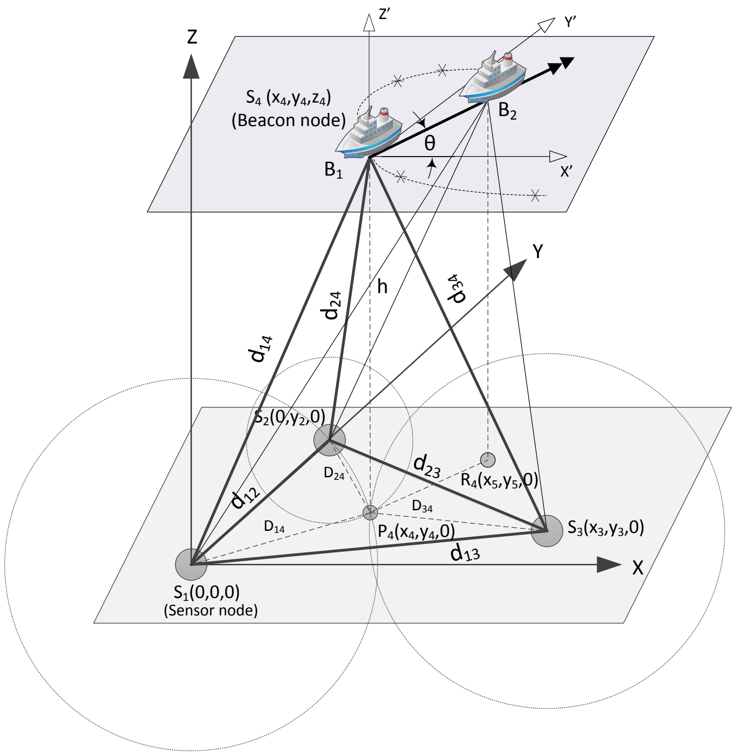

Fig. 5.6 Bearing determination

5.3 Simulation and Analysis

In order to validate the mathematical model, the proposed method has been simulated using Matlab for a problem domain depicted earlier with 150m depth where a single beacon node is capable of determining the coordinates and bearing of the submerged sensors. A group of three sensors are placed at (0,0,0), (0,75,0), and (80,40,0) and the mobile beacon moved randomly in a plane, which is parallel to the bottom plane where the sensors are. The coordinates of the sensors are randomly chosen, while for computational simplicity one of the sensors is placed at the origin and the other one on the axis of the problem domain as discussed earlier. While computing the coordinates of the sensors S_2

and S_3 with respect to S_1, Gaussian noise is added with the true Euclidean distances between beacon and sensors.

5.3.1 Coordinates and Bearing with Euclidean Distances

In our proposed approach the number of beacons required is just one that floats on the surface of the water and minimum of three sensors - a recognized number in monitoring for analyzing environment with sensors. In case of numerous sensors, three at a time will be localized and so on. Besides, our method is capable of determining 3D coordinates with respect to the beacon node with bearing information which gives a better comprehension regarding the location of the sensors, since coordinates of the beacon node could be known with the help of GPS.

In order to validate the mathematical model a group of three sensors are placed randomly on the XY plane and the mobile beacon is steered above, which is assumed to be in parallel state to the bottom plane where the sensors are deployed. While the coordinates of the sensors are chosen randomly, for computational simplicity one of the sensors is marked as the origin and the other one on the Y-axis of the problem domain. Eventually the third sensor could be positioned in any point of XY plane as discussed. To get distance measurement from six different positions of the beacon, it has been randomly moved around to six different coordinates in different orientations. However, mobility of the submerged sensors is not considered in the proposed mathematical model. At first to prove the mathematical model, true Euclidean distances between the sensors and beacon are considered while computing the coordinates of the sensors S_2 and S_3 with respect to S_1.

Simulation results suggest that if the distances between beacon and sensors are true Euclidean then the positional errors are negligible. For a problem domain of 150m depth, positional errors are in 10^{-12} to 10^{-14}m range. For a sensor of 0.5m to several meters in length, the generated error is quite negligible, which in turn validates the proposed mathematical model. Fig. 5.7, Table 5.5 and 5.6 show scrupulous accuracy and precision in position detection. Positional and bearing errors are negligible for different orientation of the beacon; these conspicuous negligible errors have been generated due to linearization of a system of nonlinear equations.

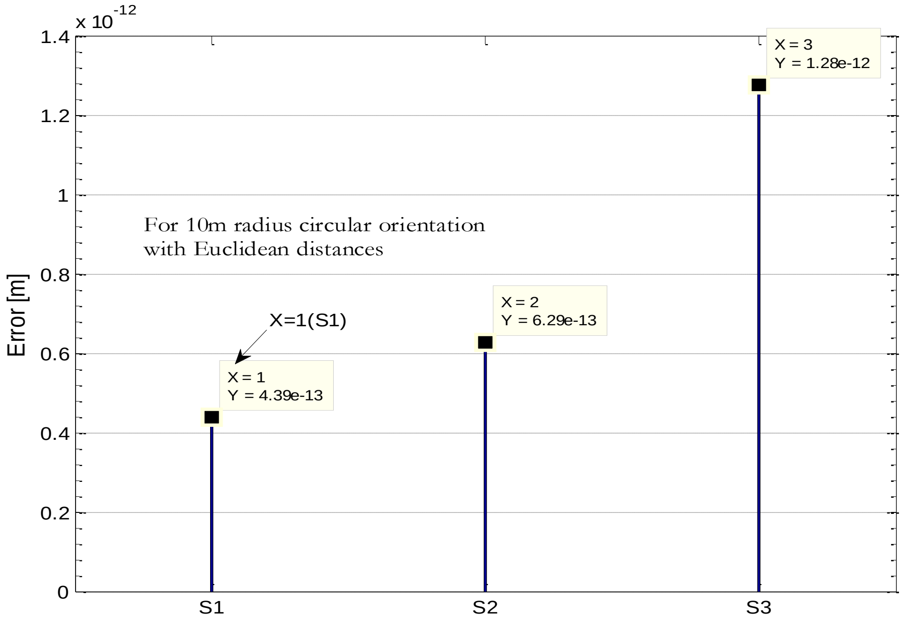

Fig. 5.7 Positional errors with 10m circular orientation with Euclidean distances

Simulation also suggests that the orientation of the beacon while measuring distances can be any form except in straight line; measurements in straight line push the matrix to be singular and unsolvable. Whereas, the arbitrariness of the orientation of a mobile beacon on the surface of the water is very natural, hence Archimedean spiral and circles of different radius have also been explored to see the validation of the proposition.

Table 5.5 Bearing and positional errors with respect to beacon for 36^o (Euclidean distances)

Circular orientation (radius)	**Bearing** (originally)	**Bearing** (computed)	**Positional Error** S_1(m)	S_2(m)	S_3(m)
5m	36^o	35.976^o	1.10×10^{-12}	1.98×10^{-12}	3.47×10^{-12}
10m	36^o	35.976^o	4.38×10^{-13}	8.95×10^{-13}	1.60×10^{-12}
15m	36^o	35.999^o	1.45×10^{-13}	2.13×10^{-13}	1.13×10^{-12}
20m	36^o	35.993^o	7.10×10^{-15}	5.68×10^{-14}	7.32×10^{-13}
50m	36^o	35.994^o	7.10×10^{-15}	4.26×10^{-14}	1.03×10^{-13}

Table 5.6 Bearing and positional errors with respect to beacon for 72° (Euclidean distances)

Archimedean Spiral (single turn increase)	**Bearing** (originally)	**Bearing** (computed)	**Positional Error**		
			S_1(m)	S_2(m)	S_3(m)
5m	72°	72.068°	6.04×10^{-13}	1.17×10^{-12}	3.20×10^{-12}
10m	72°	72.038°	4.57×10^{-13}	9.23×10^{-13}	2.59×10^{-12}
15m	72°	72.012°	8.55×10^{-13}	1.66×10^{-12}	3.12×10^{-12}
20m	72°	72.031°	5.74×10^{-13}	1.13×10^{-12}	7.73×10^{-13}
50m	72°	72.007°	1.01×10^{-13}	2.55×10^{-13}	8.55×10^{-14}

5.3.2 Coordinates and Bearing with Gaussian Noise

Fig. 5.8 shows the computed coordinates of the sensors with Gaussian noise in distance measurements as the precision of distance measurements is one of the prime factors for accurate coordinate determination. Coordinates of the sensors have also been determined after incorporating Gaussian noise to distance measurements with a distribution of mean 0 and variance 1.

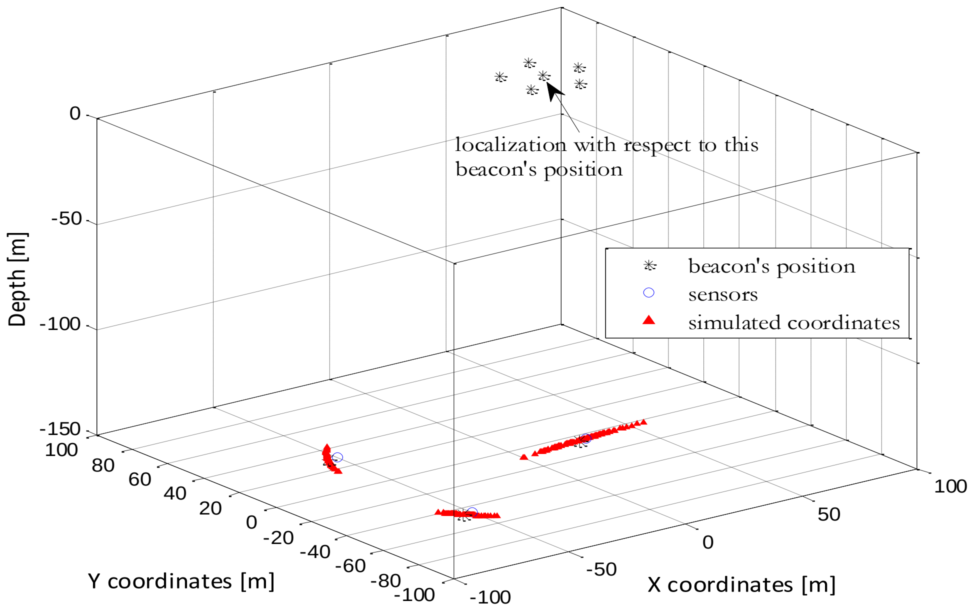

Fig. 5.8 Calculated sensors positions with respect to actual coordinates

Positional errors for sensors S_1, S_2 and S_3 are shown in Fig. 5.9 - 5.11 with respect to beacon at the surface; produced mean positional errors of the submerged sensors are around 3m range without even omitting outliers, which is pretty good comparing the sizes of the submerged sensors as sensors can vary from 1-5m range in cases of automated unmanned vehicles (AUVs) or unmanned underwater vehicles (UUVs). Table 5.7 and 5.8 summarize bearing and positional errors for different orientations of the beacon, which shows bearing errors also remain within 0.21-3.38^0 variation.

Besides, simulation also suggests spans of the beacon's orientation do not affect the determination of coordinates, measurements can be taken in a close proximity - so that the errors generated from mobility of the sensors can be minimized. As the model generates negligible positional error with Euclidean distances, it is conspicuous that distance measurements are the limiting factor for pin pointing the sensors and distance measurements errors can be minimized using different signals and methods.

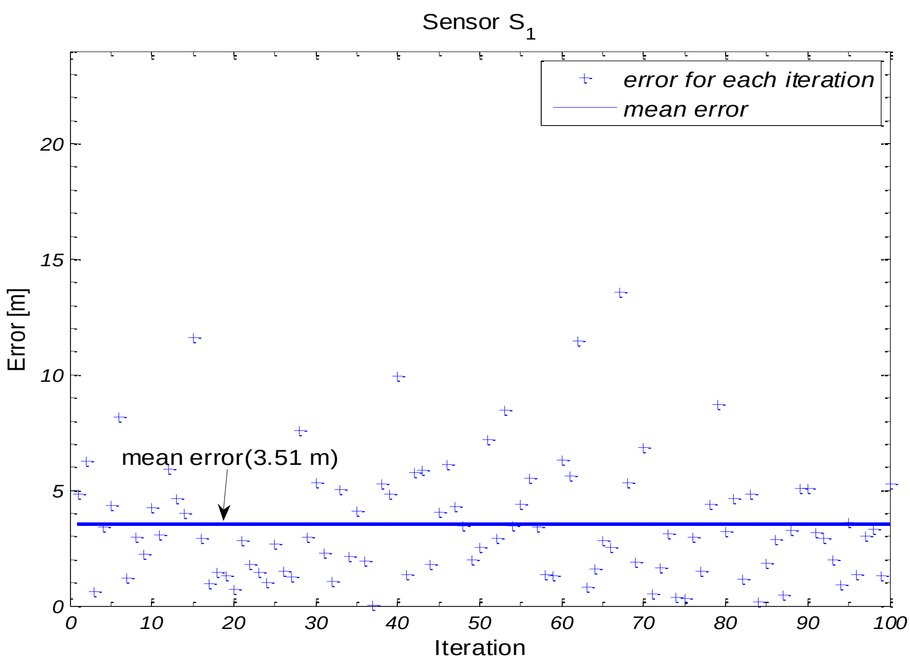

Fig. 5.9 Distance error for sensor S_1

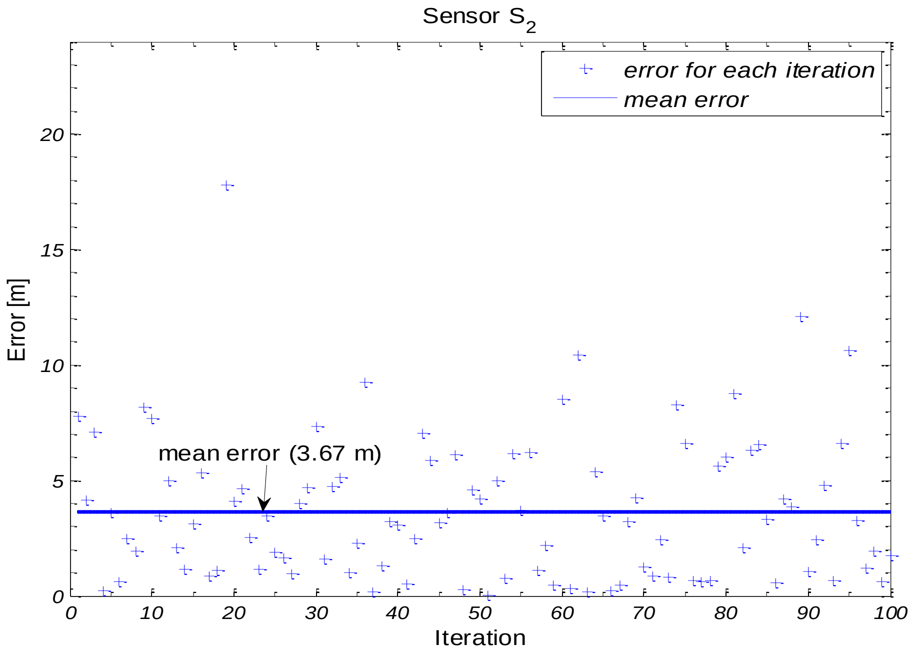

Fig. 5.10 Distance error for sensor S_2

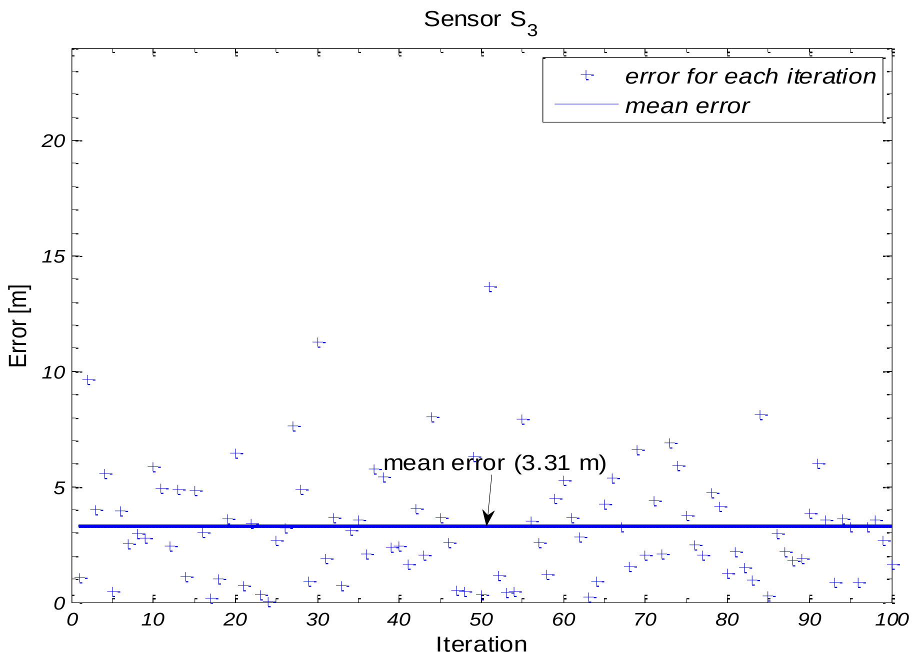

Fig. 5.11 Distance error for sensor S_3

Table 5.7 Bearing and positional errors with respect to beacon for 36° (Gaussian noise)

Circular orientation (radius)	**Bearing** (originally)	**Bearing** (computed)	**Mean positional error** S_1(m)	Std.	S_2(m)	Std.	S_3(m)	Std.
5m	36°	37.18°	3.68	2.82	3.67	2.81	3.08	2.37
10m	36°	38.49°	3.63	3.00	3.62	2.99	3.03	2.50
15m	36°	33.79°	4.70	3.01	4.69	3.00	3.93	2.54
20m	36°	39.38°	4.13	3.95	4.12	3.94	3.46	3.39
50m	36°	35.53°	4.09	2.76	4.08	2.76	3.42	2.32

Table 5.8 Bearing and positional errors with respect to beacon for 72° (Gaussian noise)

Archimedean spiral (radius)	**Bearing** (originally)	**Bearing** (computed)	**Mean positional error** S_1(m)	Std.	S_2(m)	Std.	S_3(m)	Std.
5m	72°	72.21°	3.78	2.58	3.77	2.57	3.17	2.17
10m	72°	72.79°	4.24	3.18	4.23	3.17	3.56	2.67
15m	72°	71.14°	4.02	2.68	4.01	2.68	3.37	2.24
20m	72°	70.58°	4.57	3.23	4.56	3.22	3.83	2.74
50m	72°	72.59°	3.25	3.36	3.24	3.35	2.72	2.84

The positional error of the sensors with Euclidean distances between beacon and sensors is very negligible, which proves the validity of the mathematical model. Simulation also suggests the span of the surfing area has no effect on coordinates and bearing determination process of the sensors. However, the precise distances between beacon and the sensors are the determining factor of accurate coordinates.

5.3.3 Effect of Different Orientation of the Beacon

Different orientations of the mobile beacon have been also explored, straight line to angular fashion, circular to Archimedean spirals of different radius (5-50m) as well as in random fashions. The arc length (l) of Archimedean spiral is considered according to (5.15) and (5.16).

$$r = a + b\theta \,, \tag{5.15}$$

$$l = \int_{\theta_1}^{\theta_2} \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2}\, d\theta \,. \tag{5.16}$$

here, r is the distance from origin, θ_1 to θ_2 spans from inner and outer radius of the spiral respectively.

The orientation of the beacon's mobility followed as fashioned in Fig. 5.12 and Fig. 5.13; the results suggest orientation of the beacon has no significant effect except the orientation in a straight line.

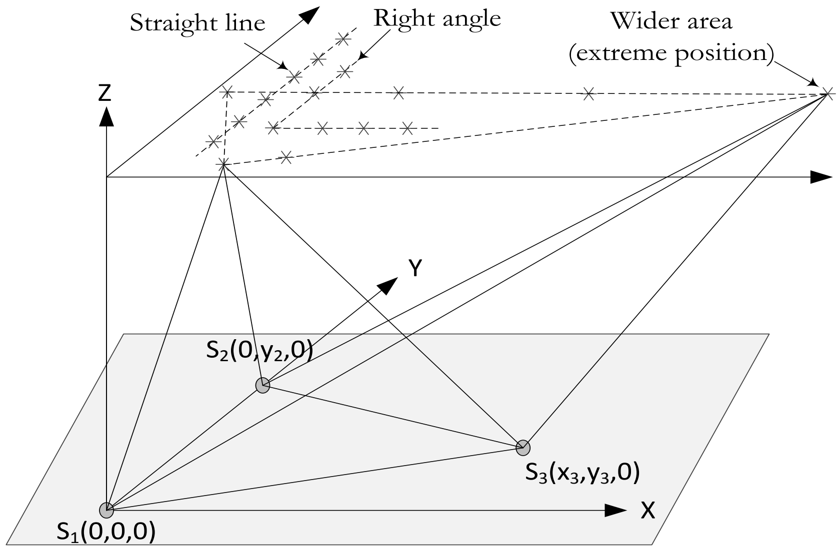

Fig. 5.12 Different orientations of the beacon's movement while measuring distances

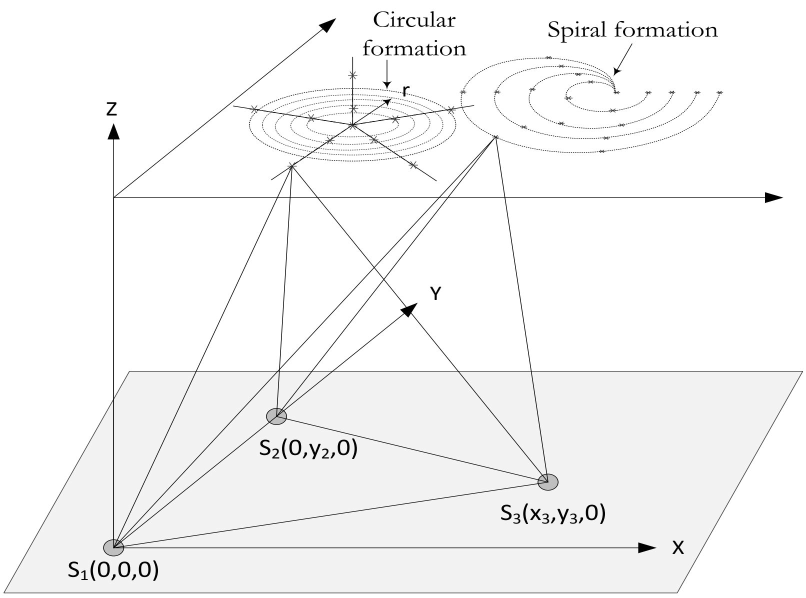

Fig. 5.13 Different orientations of the beacon's movement while measuring distances

We have also found that straight line or right angle movement of the beacon while taking measurement pushes the matrix of the model to be singular without converging. In reality this formation is quite impossible to occur where movement of the beacon (boat/buoy) would be random by nature due to drift and steering.

5.4 Conclusions

Proposed method is designed to determine coordinates and bearing of submerged sensors for a water column keeping a beacon floating at the water surface. This pragmatic configuration of the proposed method does not require any preinstalled infrastructure, whereas capable of determining coordinates in dynamic fashion with a single beacon. Simulation validates the mathematical model of coordinates determination from acquired distances from the beacon to the submerged sensors. In Matlab beacon and sensors are placed in Cartesian coordinates and distances are measured between those points to find the Euclidean distances. The simulation is performed without emulating the water column as we haven't covered distance determination techniques in this paper. In reality distances between beacon and the deployed sensors are presumed to be done by determining the flight time of the acoustic signals; hence the multipath phenomenon or propagation model of signals is out of the scope of this paper.

The expanded Cayley-Menger determinant to solve volume of tetrahedron created by the single beacon and three submerged sensors is non-linear, as degree-of- freedom of non-linear equations does not guarantee a solution; we tend to linearize the equation and get the number of six unknown variables, which is why we need six measurements to solve the system of linear equations. While considering Euclidean distances with circular and Archimedean spiral orientations of the beacon with radius ranging from 5-50m, the positional error and bearing of the submerged sensors are very negligible, positional error in the picometer range and fraction of a degree in bearing is due to linearization of the determinant. However, the positional error increased to 3-4m range and bearing remains within couple of degrees once Gaussian noise in distance measurements is applied. Considering 150m simulated water column and the size of the sensors and AUV or UUV - achieved errors are in acceptable range.

Chapter 6

EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

This chapter focuses on the conducted experiment and customization of devises to fit our proposed distance measurement algorithm and coordinates determination. It also compares the results with other localization algorithm and put forwards an extensive analysis on how this experimental setup can be used in any environment to localize sensors.

6.1 Introduction

The conducted experiment is done in the terrestrial environments in the lab with compatible sensors to prove the proposed mathematical model for coordinates determination. Flight time of the acoustic signal is used to calculate the distances between the beacon and sensors. To achieve that first of all same scenario as the problem domain described in section 4.2 has been emulated; keeping an acoustic sensor (i.e., beacon) over the table top and three other sensors on the table. As we have used wired sensors in the experiment, time synchronization between the beacon and the underneath sensors is done with electric signals instead of radio. The same orientation can be applied in the underwater environment with appropriate sensors that have both radio and acoustic signals capability and are not susceptible to underwater environment. The limitations of off the shelf acoustic sensors are also identified and possible parameter changes will be focused in this chapter in case of underwater experiments.

6.2 Experimental Setup

Experiment has been conducted in compliance with the orientation of the Fig. 5.2. Three acoustic sensors are deployed in some predefined coordinates on the table top with acoustic signal receive capability; whereas a single acoustic sensor (beacon) is put above those with acoustic transmit and receive capability. The communications after determining the flight time of the generated acoustic pulse from the beacon to deployed table top sensors are done with electrical signal as sensors are connected to Arduino board directly. As general communication between beacon and sensors are out of the scope of our research problem, communication is mainly done with the electrical signals; however acoustic signal is used to determine the flight time from the beacon to deployed table top sensors.

6.2.1 Devices and its Limitations

The experiment has been performed with an Arduino board connected to four HC-SR04 ultrasonic sonic sensors as in Fig. 6.1. Ultrasonic sensors are mainly used to determine distances with bouncing technique, which is generated signal bounces back from the nearest obstacles that are positioned in front of the sensor. If the object's position is placed in angular fashion, i.e., is positioned not right in front of the sensor, HC-SR04 sensor will not be able to receive the bounced back signal. In this experiment we have customized the sensors as such that it does not measure the distance with bouncing signal, whereas the table top sensors detect the presence of signal that has been generated by the beacon sensor at the top. The setup is elaborated in the following section. The specification and its limitation are stated in Table 6.1.

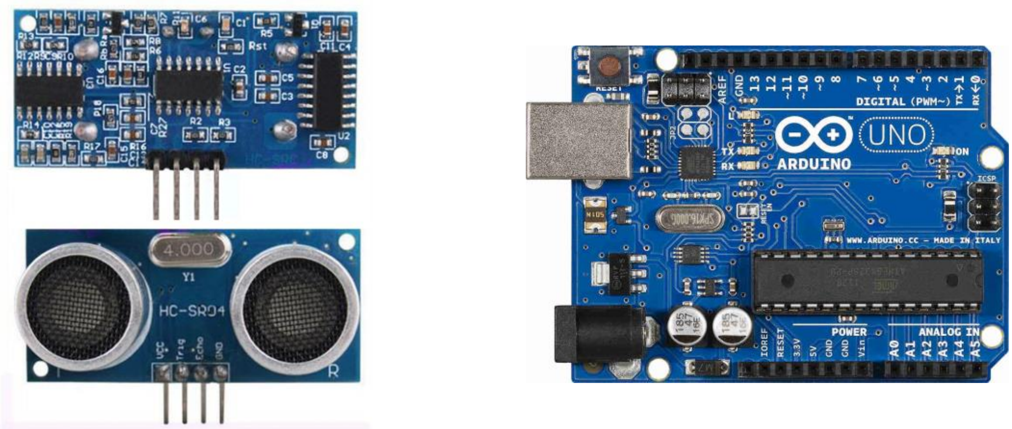

Fig. 6.1 Ultrasonic sensor and Arduino UNO board

Table 6.1 Specifications of ultrasonic sensor and Arduino Uno

Type	Pin Symbol	Pin Function Description
HC-SR04 (Ultrasonic Sensor)	VCC	5V power supply
	Trig	Trigger pin
	Echo	Receive pin
	GND	Power ground

Parameters	HC-SR04 Ultrasonic Sensor
Operating Voltage	5V (DC)
Operating current	Max 15 ma
Operating frequency	40KHz
Range	2cm – 500cm
Sentry angle	Max 12^0
High-accuracy	0.3cm
Input trigger signal	10μs TTL pulse
Echo signal	Output TTL PWL signal
Dimensions	45x20x15mm

Parameters	Arduino Uno
Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage	6-20V
Digital I/O Pins	14 (6 of them provide PWM output)
DC Current per I/O Pin	40mA
Flash Memory	32KB
SRAM	2KB
Clock Speed	16MHz

6.2.2 Description of the Setup

To determine the coordinates of the sensors, the proposed method assumes at least three submerged sensors and a floating beacon at the surface of the water column. Usual number of sensors deployed underwater varies from few to thousands to collect data in UWSNs. It is also assumed that the distance measurements between the beacon and sensors will be conducted by measuring the flight time of acoustic signals as devised in [163]. However to develop the mathematical model of coordinates determination and to perform the simulation, average speed of acoustic signal is not a necessary parameter to be considered. It is worth noting here that as distance determination is out of the scope of this work, signals propagation model and the multipath fading phenomenon of signals due to obstruction and other factors left undiscussed.

While taking multiple distance measurements as required by the proposed model we also assume that the plane on which beacon surfs and the plane created by the three submerged sensors are in parallel state. In reality not being in the parallel states would contribute to errors in coordinates, though the surfing area of the beacon while taking multiple measurements can be in close proximity to mitigate non-parallel effects. The proposed mathematical model in this work does not incorporate non-parallel effect on coordinates and bearing determination. For simplicity, the model also assumes that the submerged sensors are stationary during distances measurements process. The general properties of a transducer or beacon have the capability of generating and receiving signals, whereas sensors may have the restricted capability. A solvable configuration of one beacon with three submerged sensors is denoted in Fig. 5.2. Fig. 6.2 and 6.3 show the actual setup of the experiment with aforesaid ultrasonic sensors.

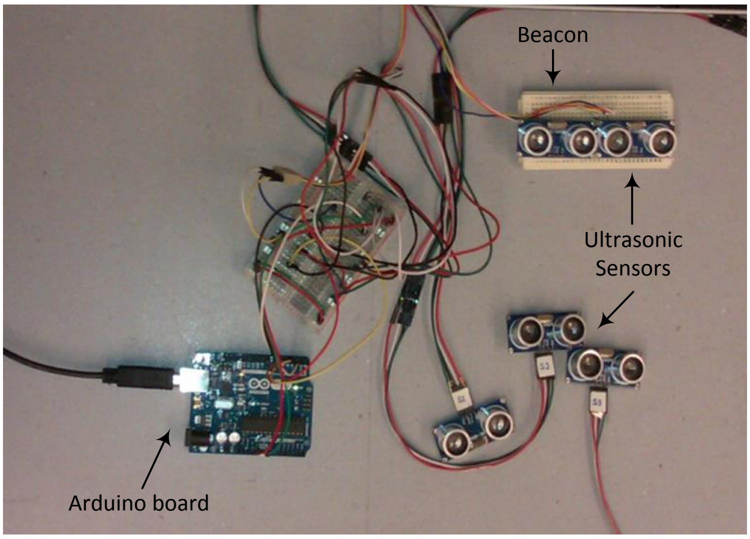

Fig. 6.2 Connection of ultrasonic sensors with Arduino board

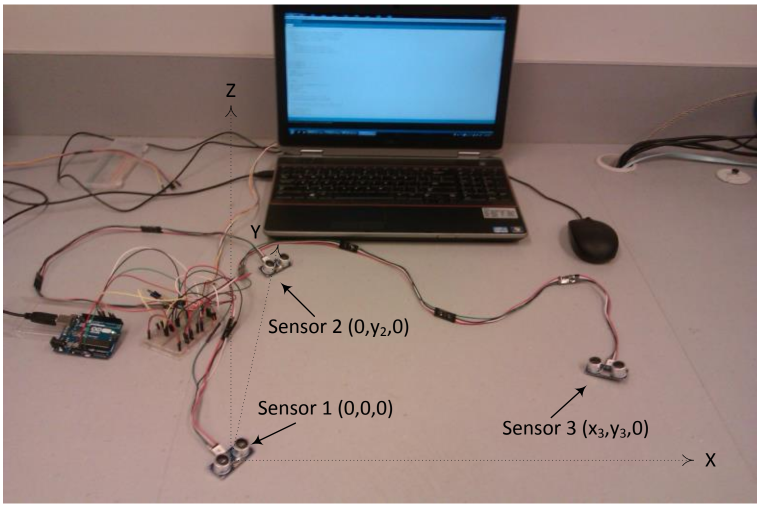

Fig. 6.3 Coordinates determination of three sensors

6.2.3 Distance Calculation

Distances between the beacon (sensor over the table top) and sensors (Sensor 1, Sensor 2 and Sensor 3) on the table are determined in the experiment by calculating the flight time of generated acoustic signals from beacon. Ultrasonic sensors used in the experiment generate TTL impulses in 40KHz frequency and 3 sensors at the bottom receives the pulses and record the time of arrival. Speed of acoustic signals varies on multiple factors according to Eq. (6.1) (Laplace's adiabatic assumption) as in [164].

$$v_{acoustic(air)} = \sqrt{\frac{\gamma P}{\rho}} \tag{6.1}$$

where γ, P and ρ are the specific heat ratio, pressure, and density of the medium respectively. Eq. 6.1 is then modified to Eq. 6.2 and speed of sound is calculated for a standard atmosphere, under a barometric pressure of 101.325kPa, at a temperature of 0^{o} C (T_0=273.15K), and numerical value of the universal gas constant R is 8314.48 J kmol $^{-1}$K^{-1}.

$$v_{acoustic(air)} = \sqrt{\frac{RT\gamma}{M}} \tag{6.2}$$

According to [164], v_0 is 331.29m/s in standard dry air at and at a barometric pressure of 101.325kPa. For our experiment in the lab with normal terrestrial environment sound speed is considered to be 340m/s, i.e. it takes 29µs to travel 1cm of distance. Once the flight time of the signal is measured with Arduino board and ultrasonic sensors, distances between them are calculated by multiplying flight time with 340m/s. Those measured distances are then put into the proposed mathematical model using Matlab to determine the coordinates of the sensors. It is worth noting that clocks of all the sensors including the beacon at the top are synchronized as it is connected to the same Arduino board; besides the pulse generation time and a sample of generated impulse by the beacon is made available to the sensors to determine the signals' arrival time as soon as it travel the shortest Euclidean distances.

6.3 Experimental Results

Two different scenarios were experimented each with four trials. For each scenario, beacon and underneath sensors were kept in different orientations and heights. Table 6.2 and Table 6.3 portrays the elaborated distances achieved in every trial and computed coordinates and positional errors for the sensors (S_1, S_2 and S_3) are shown in Table 6.4.

Scenario 1: Original Coordinates of sensors: S_1: (0,0,0); S_2: (0,20,0); S_3: (30,15,0)

Table 6.2 Experimental results for scenario 1

Trial 1

readings	S1	S2	S3
R1	54.14	52.31	50.36
R2	57.96	52.65	51.10
R3	51.32	50.56	52.87
R4	61.11	52.49	55.71
R5	59.90	58.57	48.99
R6	60.14	55.04	50.17

Calculated Coordinates:
S1: (0,0,0)
S2: (0,19.83,0)
S3: (29.58,14.94,0)

Trial 2

readings	S1	S2	S3
R1	62.57	57.27	52.20
R2	60.31	54.78	53.17
R3	53.39	52.60	55.01
R4	63.58	54.62	57.96
R5	62.32	60.94	50.98
R6	56.34	54.42	52.40

Calculated Coordinates:
S1: (0,0,0)
S2: (0,20.55,0)
S3: (30.88,15.45,0)

Trial 3

readings	S1	S2	S3
R1	60.76	55.20	53.57
R2	56.76	54.83	52.79
R3	53.80	53.00	55.43
R4	64.06	55.03	58.40
R5	62.79	61.41	51.36
R6	63.04	57.71	52.60

Calculated Coordinates:
S1: (0,0,0)
S2: (0,20.73,0)
S3: (30.93,15.42,0)

Trial 4

readings	S1	S2	S3
R1	61.82	53.11	56.36
R2	58.64	53.27	51.70
R3	51.92	51.15	53.49
R4	54.78	52.92	50.95
R5	60.60	59.26	49.57
R6	60.84	55.69	50.76

Calculated Coordinates:
S1: (0,0,0)
S2: (0,20.01,0)
S3: (29.94,15.01,0)

Scenario 2: Original Coordinates of sensors: S_1: (0,0,0); S_2: (0,25,0); S_3: (35,10,0)

Table 6.3 Experimental results for scenario 1

Trial 1 (readings)

	S1	S2	S3
R1	65.34	62.51	53.19
R2	54.94	58.15	56.49
R3	55.90	54.13	58.85
R4	58.63	57.91	54.44
R5	62.95	60.46	53.42
R6	60.32	55.26	57.25

Calculated Coordinates:
S1: (0,0,0)
S2: (0,26.12,0)
S3: (36.55,12.54,0)

Trial 2 (readings)

	S1	S2	S3
R1	59.85	57.26	48.71
R2	50.32	53.25	51.74
R3	53.70	53.04	49.86
R4	51.20	49.57	53.90
R5	57.65	55.37	48.92
R6	55.25	50.62	52.43

Calculated Coordinates:
S1: (0,0,0)
S2: (0,23.72,0)
S3: (33.26,12.94,0)

Trial 3 (readings)

	S1	S2	S3
R1	56.77	52.01	53.88
R2	51.71	54.73	53.17
R3	55.18	54.51	51.24
R4	52.61	50.94	55.39
R5	59.25	56.90	50.28
R6	61.50	58.84	50.06

Calculated Coordinates:
S1: (0,0,0)
S2: (0,24.53,0)
S3: (34.33,12.63,0)

Trial 4 (readings)

	S1	S2	S3
R1	62.36	59.90	52.92
R2	54.43	57.61	55.97
R3	58.09	57.38	53.94
R4	64.74	61.94	52.69
R5	55.38	53.62	58.31
R6	59.76	54.75	56.72

Calculated Coordinates:
S1: (0,0,0)
S2: (0,25.81,0)
S3: (36.15,13.64,0)

Table 6.4 Positional errors of the sensors for both scenarios

	Scenario 1			**Scenario 2**		
	S_1(cm)	S_2(cm)	S_3(cm)	S_1(cm)	S_2(cm)	S_3(cm)
Trial 1	0	0.17	0.42	0	1.12	2.98
Trial 2	0	0.55	0.99	0	1.28	3.42
Trial 3	0	0.73	1.02	0	0.47	2.71
Trial 4	0	0.01	0.06	0	0.81	3.81

For sensors with dimension 4.5x2x1.5cm, positional error 0.01-3.81cm is quite outstanding. As simulation in sec. 5.3.1 validates the negligible error with Euclidean distances, it is now conspicuous that the precise the distances are measures from the beacon to the deployed sensors the lesser the positional errors are. Table 6.5 shows the comparison and characteristics of different underwater localization algorithms for their own problem domain.

Table 6.5 Comparison between different localization schemes

Localization schemes		No. of initial Ref. nodes	Ref. point	Inter-node time sync	Comm. Costs	Accuracy
LSLS	Projection based with desirable properties of UPS	3 surface	static	yes	5% active	0.25
USP	Projection based	3 surface	static	yes	3msg/node	0.43
LSL	Multiple Surface buoys and submerged anchors	25	static	yes	60msg/node	0.40
SLMP	Improved LSL	50	static	yes	8msg/node	0.16
AUV-aided (2D)	1 AUV (underwater location needs to be known)	1	mobile	no	70msg/node	0.167
DNRL	Surface buoy (Dive-aNd-Rise)	25	mobile	no	5msg/node	0.23
LSL-DET	Surface buoy with DETs	37	mobile	yes		0.0167
CSMB (3D) (Proposed)	Surface buoy (Adhoc)	1 surface	mobile	no	2msg/node	0.44

6.4 Analysis

Proposed method is designed to determine coordinates of submerged sensors for a water column keeping a beacon floating at the water surface. This pragmatic configuration of the proposed method does not require any preinstalled infrastructure, whereas capable of determining coordinates in dynamic fashion with a single beacon. This experimental configuration can be applied in the real world as well; where the coverage area would depend on the type of sensors used as beacon. The HC-SR04 ultrasonic sonic sensors used in the experiment has 12^{o} sentry angle with 500cm range, this coverage can be extended by customizing sensors, which would be used as beacon for the real applications. In the real world, a single boat/buoy (beacon) will be used to explore and/or monitor the deployed sensors, for that reason the same configuration is used in the experiment to emulate the situation. The range of signals and sensor's sentry angle will regulate the coverage area. Of course, for the case of radio signals – coverage area would be much smaller (~323m) than the coverage area of acoustic signals (>>km). As most of the marine explorations take place in the vicinity of coastal area, which is 100-200m in depth, use of radio signals will serve our research objective partially. In case of deep sea exploration where depth of the problem domain is larger than propagation distance of radio signals underwater, only acoustic signals will be used to measure the distances between beacon and sensor nodes.

Simulation validates the mathematical model of coordinates determination from acquired distances from the beacon to the submerged sensors. The acquired result has been reinforced by experimenting three ultrasonic sensors on the table top and a beacon above those emulating the configuration as depicted earlier. Distance measurements between beacon and underneath sensors are calculated by calculating the flight time of the acoustic signals. This way of measuring distance helps us to avoid multipath fading affect as present in RSSI. It also shows that it is possible to calculate the distances between sensors as the pulses travel the shortest Euclidean distance. Figure 3 shows the intended distance to be measured.

6.4.1 Problems and Challenges Encountered in Experiments

Mathematical model has been validated in simulated environment concluding the accuracy of the distance measurements are the limiting factor of the precise coordinates determination. Different scenario has been chosen for the experiment and each scenario is tested multiple times. In each test we needed to read the distances six times from different positions of the beacon. While reading the values time to time some readings were such that it does not comply with the real distance, and eventually did not converge in Matlab. In those cases we had to go for another test that ultimately converges. In each reading the measured distances for S_1, S_2 and S_3 have to be consistent.

The off the shelf ultrasonic sensors has 12^o sentry angle which limits the beacon's movement span. Besides the built-in Arduino '*microsecondsToCentimeters*' function needed to be changed to 'double' to acquire more precise timing as the experiment is taken place where the maximum distances between beacon and deployed sensors are less than 80cm range. One other challenge we faced while experimenting with Arduino board is to process the generated ultrasonic pulses that are received by the sensors to calculate inter distances. The '*pulseIn*' function usually takes more than 20ms to process the received pulse, whereas it takes only 2.32ms to travel 80cm (approximate max distance for the experimental domain); as a result by the time it finishes pulse processing for the nearest sensor from the beacon and starts processing pulses for other sensors, it is then too late for the pulses to be on the flight. To mitigate this problem we had to generate two other 10μs pulses for rest of the two sensors in 50ms interval. So within around 100ms all three pulses are generated, this fraction of a second will have no effect on the stationary sensor nodes scenario; however will have negligible effect in cases of mobility. This 'absence of pulse' situation is due to sharing the Arduino board for processing the pulses for all three sensors. On the other hand, this situation in underwater environment can be avoided having individual processing board attached to each deployed sensors.

Produced positional errors of the submerged sensors are around 6cm range, which is pretty good comparing the sizes of the deployed ultrasonic sensors with dimensions (4.5x1.5x1.5cm) used in the experiment. In Matlab beacon and sensors are placed in Cartesian coordinates and distances are measured between those points to find the Euclidean distances. The simulation is performed without emulating the water column as we haven't covered distance determination techniques in this work. In reality distances between beacon and the deployed sensors are presumed to be done in reality by determining the flight time of the acoustic signals; hence the multipath phenomenon or propagation model of signals is out of the scope of this paper.

The positional error of the sensors with Euclidean distances between beacon and sensors is very negligible, which proves the validity of the mathematical model. Simulation also suggests the span of the surfing area has no effect on coordinates determination process of the sensors. However, the precise distances between beacon and the sensors are the determining factor of accurate coordinates. We have also found that straight line or right angle movement of the beacon while taking measurement pushes the matrix of the model to be singular without converging. In reality this formation is quite impossible to occur where movement of the beacon (boat/buoy) would be random by nature due to drift and steering.

The expanded Cayley-Menger determinant to solve volume of tetrahedron created by the single beacon and three submerged sensors is non-linear, as degree-of- freedom of non-linear equations does not guarantee a solution; we tend to linearize the equation and get the number of six unknown variables, which is why we need six measurements to solve the system of linear equations. While considering Euclidean distances with circular and Archimedean spiral orientations of the beacon with radius ranging from 5-50m, the positional error of the submerged sensors are in very negligible picometer range, which is generated due to linearization of the determinant.

6.4.2 Limitations Identified

Some limitations identified in this research work are detailed in the following sections.

6.4.2.1 Determination of Average Speed of Sound in a Water Column

As of now, average speed of sound has been determined for a specific water column. For the problem domain as depicted in Fig. 4.2, it is possible for the sensors to be located anywhere on the bottom plane, i.e. angular stand of the sensors with respect to beacon or vertically underneath the beacon. So we have proposed a technique to calculate the average speed of acoustic signal for each sensors and beacon pairs. The environmental variables that affect acoustic speed as depicted in [165] might be different at the vicinity of each sensors; so would be the average speed of acoustic signal for each pairs. Preliminary simulated results on average acoustic speed has been published in [166], where Gaussian noise has been added to bottom temperature reading only whereas all other variables will acquire noise in some extent. In future we shall discuss the procedure of how the variables will be measured and collected. We also need to find how the speed is affected when the Gaussian noise is applied to all the variables, like temperature, depth and salinity of the water column. Besides, we intend to explore the variation in average acoustic speed in case of the linearity of the variables' value of the water column is not maintained. So far, this aforesaid limitation has been identified and will be addressed in future.

6.4.2.2 Determination of Coordinates of the Stationary Sensors

As of today, mathematical model and simulation results of coordinates of the sensors with respect to one sensor (presumed origin) are determined in [163]; besides, mathematical model of coordinates of sensors with respect to the beacon have been developed too. In the model, voluntary and/or involuntary mobility of the nodes were not considered; so far underwater sensor nodes are considered to be stationary and beacon node has the ability to steer on the surface of the water. In future, the effect of the mobility of the nodes on the coordinates will be measured and compared. Until now, the plane created by the underwater sensors and the plane on which the beacon steers are considered to be parallel; in future we intend to explore and propose a solution to identify the degree of parallel state of the planes and how they affect coordinate determination.

6.4.2.3 Flexibility of the Problem Domain

The computable distances between the beacon and sensors will be examined. Because of the use of radio and acoustic signals in distance determination, propagation distance of radio signal would be the limiting factor of coverage area of the problem domain. If the size of the problem domain is beyond the ability of radio signal's coverage, we have to switch to acoustic signal to help measure the distances. This method will be explored in the coming time frame of candidature.

In case of mobile sensors, the range of radio or acoustic signals will regulate the coverage area. Of course, for the case of radio signal – coverage area would be much smaller than the coverage area of acoustic signal. As most of the marine explorations take place in the vicinity of coastal area, which is 100-200m in depth, use of radio signal will serve our research objective partially. In case of deep sea exploration where depth of the problem is larger than propagation distance of radio signal underwater, only acoustic signal will be used to measure the distances between beacon and sensor nodes. Depending on the coverage area - movement of the deployed sensors can be regulated in case of voluntary mobility (directed) of the AUVs or UUVs; or can be defined in case of involuntary mobility (undirected) of the sensors.

6.4.2.4 Complexity of Data Collection

Collecting data is a complex task; in our method it requires multiple variables (temperature, depth, salinity) measurement around the sensors and beacon. As the speed of acoustic signal in the water depends on temperature, depth and salinity; we need to collect these values for the water column of the problem domain. It is not as convenient to measure the values around the deployed underwater sensors due to accessibility and data communication as it is around the beacon. Temperature and salinity around beacon can be measured easily while depth of the beacon can be predetermined from the water surface. Besides, temperature and salinity around the underwater sensor nodes can be measured with temperature and salinity sensors that will be attached with the nodes beforehand. Depth can be measured by converting pressure at the sensors into depth following equation as in [155].

In future, we will analyze these factors and propose method to transfer data from sensor nodes to beacon. The ability of sensors to communicate with beacon will be explored too; merits and demerits of radio and acoustic signals underwater will be analyzed for data communication.

6.4.2.5 Effect of Errors in Variables Measurement

The whole process of coordinate determination is done in two parts: distance determination between beacon and sensors, and coordinates determinations. While determining distances, multiple variables measurement is necessary both at the beacon and sensor nodes. As the speed of acoustic signal is very much dependent on the correctness of the measured values; in future we will explore which variable is more susceptible in acoustic speed determination. Preliminary experiments suggest that temperature is more crucial than depth and salinity for shallow water. We will also examine which variable measurement is more error prone.

6.4.3 Coordinates of Mobile Sensors

As of now coordinates of the sensors are determined considering stationary sensors. As the voluntary or involuntary mobility of the sensors are present, in our future research, we would like to incorporate the effect in coordinate determination.

Typically, localization of mobile sensors is performed in order to track them, or for navigational purposes. However, when sensors are mobile, we encounter additional challenges and must develop methods to address them. One of these challenges is localization latency. If the time to perform the localization takes too long, the sensor will have significantly changed its position since the measurement took place. For example, robot navigation requires periodic position estimates in order to derive the proper control outputs for wheel angular velocity. If the robot is traveling at 1m/s and the localization algorithm takes 5 seconds to complete from the time the ranging measurements were taken, the robot might be 5 meters off from its intended position. Mobility may also impact the localization signal itself. For example, the frequency of the signal may undergo a Doppler shift, introducing error into the measurement. Doppler shifts occur when the transmitter of a signal is moving relative to the receiver.

As mobility of the sensors could be directed (voluntary) and/or undirected (involuntary), following sections investigates, analyze the mobility pattern and propose primary localization solutions.

6.4.3.1 Voluntary Mobility (Directed)

The mobility of AUVs and UUVs are somewhat directed and voluntary. AUV is a robot which travels underwater without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles, a classification that includes non-autonomous remotely operated underwater vehicles (ROVs) – controlled and powered from the surface by an operator/pilot via an umbilical or using remote control. Until relatively recently, AUVs have been used for a limited number of tasks dictated by the technology available. With the development of more advanced processing capabilities and high yield power supplies, AUVs are now being used for more and more tasks with roles and missions constantly evolving. The oil and gas industry uses AUVs to make detailed maps of the seafloor before they start building subsea infrastructure; pipelines and subsea completions can be installed in the most cost effective manner with minimum disruption to the environment. The AUV allows survey companies to conduct precise surveys of areas where traditional bathymetric surveys would be less effective or too costly. A typical military mission for an AUV is to map an area to determine if there are any mines, or to monitor a protected area (such as a harbor) for new unidentified objects. AUVs are also employed in anti-submarine warfare, to aid in the detection of manned submarines. An example of this is the AN/BLQ-11. Scientists use AUVs to study lakes, the ocean, and the ocean floor. A variety of sensors can be affixed to AUVs to measure the concentration of various elements or compounds, the absorption or reflection of light, and the presence of microscopic life. Additionally, AUVs can be configured as tow-vehicles to deliver customized sensor packages to specific locations.

To localize the mobile nodes (AUVs, UUVs), the whole process has to go through some steps, like coordination phase, measurement phase and localization phase. In coordination phase, such coordination can include notification that the localization process is about to begin, and clock synchronization, which enables received signal data to be analyzed within a common timeframe. Coordination techniques such as reference broadcast synchronization (RBS) [167] and elapsed time on arrival (ETA) [168] exist that encapsulate both notification and synchronization into a single message. These coordination methods have microsecond accuracy and require transmission of only a single message.

The measurement phase typically involves the transmission of signal by the beacon. The choice of signal modality used by sensor nodes is important for accurate localization, and depends on node hardware, the environment, and the application [169]. Localization schemes will also perform differently in different environments. If the coverage area of localization is beyond the propagation distance of radio signal underwater, acoustic signal should be used. Besides, the application itself places some constraints on signal modality. A military application, for example, in which nodes must localize under stealth conditions, would be much better off using a silent modality such as radio frequency, rather than an audible one such as acoustic. As in the case of mobility, the measurement technique as well as the whole process of computation has to be done quick enough so that the displacement of the mobile sensors are within the proximity of computed coordinates.

In coordinate determination phase, as the mobile sensors speed is known; dead reckoning [170] can be used to determine the present position of the nodes from the previous estimated position (stationary stage). In underwater, accumulated error will be less than the terrestrial because AUVs does not have those limitations which mobile vehicles have on the surface, like uneven surface, wheel slippage, dust, and other factors. When measurement data is noisy, or the system is under-defined, state estimation methods can be used. There exist a number of estimation methods, but the two main approaches are: (1) maximum likelihood estimation (MLE) which estimates the values of the state based on measured data only, and no prior information about the state is used, and (2) sequential Bayesian estimation (SBE). These approaches will be explored in future to determine the coordinates depending on the situation the problem domain persist.

6.4.3.2 Involuntary Mobility (Undirected)

Involuntary mobility of the sensors due to water current is sometimes inevitable, especially where water current is strong. However, if the water body is stagnant mobility can be negligible. Non-negligible node mobility due to harsh aqueous environments is very challenging in localization. Research in hydrodynamics shows involuntary underwater nodes mobility is closely related to water current and water temperature. It also shows that the mobility patterns of objects near the seashore demonstrate a certain semiperiodic property which is absent for objects in rivers or deep sea. As temporal and spatial correlations are inherent in such movement, it can be said that mobility is not a random process, which make their mobility patterns predictable in nature sometimes. This issue will be explored and incorporated in coordinate determination. There also exist few problems with the use of acoustic signal as the propagation of radio signal underwater is limited. The unique features of acoustic channels (high error rate, low bandwidth, and long propagation delay) cause many constraints on the localization schemes for underwater sensor networks. Traditional multihop localization schemes for terrestrial sensor networks are inefficient because of their huge communication overheads [81]. As underwater sensor networks are mobile networks most of the time and node locations change continuously, most localization schemes designed for static sensor networks need to run periodically to update the location results, as will dramatically increase the communication overhead. High localization coverage and low localization error are always desired for a localization scheme, while these performance requirements are specially challenging for underwater sensor networks with stringent resource limitation.

6.5 Conclusions

The experiment to determine coordinates of the three deployed sensors with a single beacon is performed in terrestrial environment taking speed of acoustic signals as 340m/s. Same orientation and technique can be applied in underwater environment measuring *in-situ* acoustic speed, as it varies depending on the ambient parameters. So in the underwater environment only changed factor would be the speed of acoustic signals. In this experiment HC-SR04 ultrasonic sensors have been used in Arduino environment, the customization of these sensors made it possible to measure distances even though in angular stand out of the sensors. For sensors with dimension 4.5x2x1.5cm, positional error of 0.01-3.81cm is quite outstanding.

Chapter 7

CONCLUSIONS

This chapter summarizes our main contributions and shows a number of avenues to be explored in future.

7.1 Contributions

Reliable navigation and positioning of underwater sensors are very essential for our own existence and for safety-critical purposes. Moreover, a robust and continuously available localization solution is needed regardless of the specific environment and platform. So a pragmatic approach to localize deployed sensors in dynamic fashion deemed necessary. Radio and acoustic signals are used to alleviate synchronization and distance measurement problems with addition to a pragmatic approach. Followings are the synopsis of the main contributions:

An *in-situ* distance determination technique is proposed in section 4.4 where maximum clock synchronization is achieved with radio signals for shallow problem domain as most of the marine exploration takes place in shallow water. The clock synchronization is more efficient and achievable as long as the problem domain is within the propagation distance of radio signals. In case of deep water where use of radio signals is slim, it is recommended that conventional two-way message transfer will be used to determine the inter-node distances. In the proposed method, as distance is determined by calculating the flight time of the acoustic signals, the potentiality of which has been shown in the experiment in section 6.2.3; instead of assuming underwater acoustic speed 1500m/s, an *in-*

situ method has been proposed to calculate the average speed of the signals from the beacon to the deployed sensors. Considering the dynamicity of the underwater environment and the behavior of underwater acoustic signals, *in-situ* speed determination is indispensable to minimize the errors in coordinates. Simulation results show acoustic speed for various problem domains with different combinations of environmental variable varies from 1499.8-1507.6m/s. We have also examined that average underwater acoustic speed is more susceptible to temperature difference between the beacon and sensors. Depending on the problem domain and the availability of the measurements of the environmental variables, it is possible to decide when one parameter can be neglected or becomes more prominent. If the problem domain is shallower, it is more likely that salinity difference between the beacon (surface) and sensors' area would be very less; so the salinity effect can be neglected if it is not readily available. Due to limited propagation of underwater radio signals, clock synchronization with radio can be limited within shallow water, however average acoustic speed determination from the gathered environmental variables can be utilized in any depth of water column to minimize distance error. It is vital that the distance between beacon and sensors are determined as accurately as possible; the aforesaid proposed method of coordinates determination proves that the better the distances are achieved, the better the coordinates are determined. A pilot experiment is performed in terrestrial environment with ultrasonic sensors in Arduino environment to validate the proposed method.

A mathematical model to determine the coordinates of submerged sensors with a single beacon dynamically is devised in section 5.2.1 and 5.2.2. Having a single mobile beacon at the surface without a preinstalled infrastructure is very pragmatic in nature for continuous localization of nodes. The method computes the coordinates with respect to the beacon and sensor nodes that alleviates a number of problems in the domain of localization. Mostly, the multilateration technique is used to determine the location of the sensors with respect to three or more known beacon nodes, besides incorporated nonlinear distance equations are solved in conventional method whereby degree-of-freedom does not guarantee a unique solution. Proposed method requires no preinstalled infrastructure or reference point, whereas coordinates are determined with a mobile single beacon. Moreover, Cayley-Menger determinant and linearized trilateration are used to determine the coordinates of the nodes where none of the nodes have *a priori* knowledge about its location. The computational complexity is less as it only requires two messages to be transferred in the whole localization process; moreover, all the energy hungry computations will take place at the surface node (a boat) which does not go through energy crisis as deployed sensors. The proposed mathematical model generates negligible error i.e. 10^{-12} to 10^{-14}m positional error with 0.972% variation in bearing with Euclidean distance. However, the positional error increased to 3-4m range without even omitting outliers and bearing remains within 0.21-3.38^{0} variation once Gaussian noise is applied. Considering the varying size of sensors 0.5-4m, in case of AUV or UUV, the scrupulous performance validates the potential of the proposed method.

In sections 5.2.3, how non-parallel situation between water surface and the plane created by the sensor nodes are solved. As bearing is an important piece of information in localization, with the global information of the surfaced node (boat), bearing of the underwater deployed sensors is determined. The surface node has abundance of power and energy, capable of communicating with satellite for its global position in contrast with deployed underwater sensors, which are restricted by limitations. We have also showed the effect of beacon's mobility and span on determined coordinates and bearing of the submerged nodes. Simulation also suggests that the beacon's mobility and span do not affect the coordinates and bearing determination process as long as the submerged sensors are stationary for the duration of distance measurement process. However, as determined, some specific orientations of the beacon's mobility need to be avoided to help converge.

7.2 Future Research

The work presented in this thesis could be extended in following directions despite the limitations. While taking multiple distance measurements between the beacon and sensors we assumed that the deployed sensors would be in stationary mode for a short period of time. In fact, the displacement of the sensors due to current would be insignificant in normal condition; however, following option can be exploited to overcome the extreme situations.

Mobility of the sensors. While it is reasonable to assume that nodes in terrestrial networks remain static, underwater nodes will inevitably drift due to underwater currents, winds, shipping activity, etc. In fact, nodes may drift differently as oceanic current is spatially dependent. While reference node is at the surface and can precisely be located through GPS, it is difficult to maintain submerged underwater nodes at precise locations. This may affect localization accuracy, as some distance measurements may have become obsolete by the time the node position is estimated. Moreover, motion of the sensor nodes may create the Doppler effect which is due to the relative motion of the transmitter or the receiver. In underwater applications, mobile platforms such as AUVs can move with a speed of several knots, while untethered, free-floating equipment can drift with the ocean currents which are generally slower than 1 knot. Doppler effect is related with the ratio of the relative transmitter-receiver velocity and the speed of the signal. Since the speed of sound in water is slower than speed of the electromagnetic waves in the air, Doppler effect can be more significant in UWSNs than in WSNs. Therefore, mobility introduces another challenge from the view point of communications overhead and energy-efficiency since underwater equipment are expected to be left in the ocean for several weeks or months before they are collected and recharged for their next mission.

Propagation distance of underwater radio signals. Studies show that radio signal can propagate up to 1.8-323m underwater depending upon frequencies and the propagation speed can reach up to 4.30×10^6m/s in MHz frequency. Underwater communication research has shown that transmission at 5MHz frequency is feasible in seawater up to 90m giving a data rate of 500kbps that allows duplex video and data streams. If feasible all the communication between beacon and the deployed sensor nodes could be done with radio instead of acoustic signals as done conventionally.

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